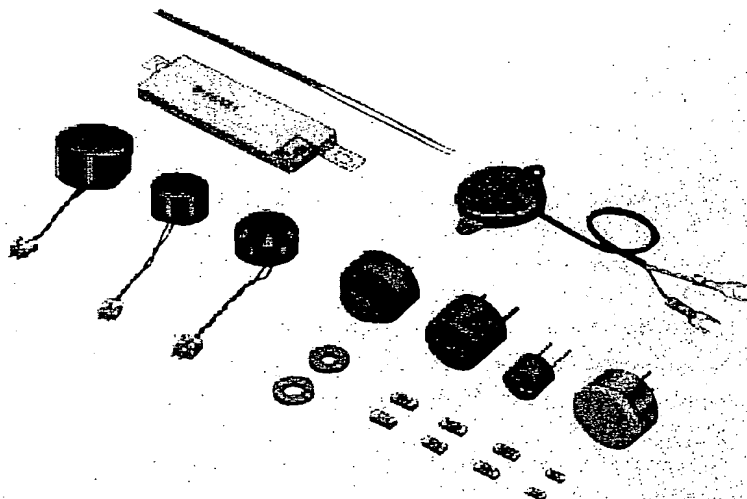


# Piezoelectric Ceramic Sensors (PIEZOTITE®)

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## PIEZOELECTRIC CERAMICS SENSORS (PIEZOTITE®)



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**Murata**

Murata  
Manufacturing Co., Ltd.

*Innovator  
in Electronics*

Cat.No.P19E-7

## **Preface**

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Recently, with the remarkable advance of electronics technology, various new products have come into existence. Until this time, the effect of electronics was seen most clearly in television, radio and other communications equipment, but as semiconductor technology, and computer technology advance, the range of electronics' effect on our lives has increased dramatically. In particular, sensor technology and the greater intelligent functions of today's microcomputers have served as a basis for the trend toward combining electronics and mechanics into what is called mechatronics.

It is not merely the equipment itself, however, that has made all this possible. Within the equipment are highly sophisticated components with unique functions which can translate electrical to mechanical energy and mechanical to electrical energy and which play a large role in today's equipment modernization and advance. These are piezoelectric components. This catalog briefly introduces the basics of piezoelectric ceramics, Murata's piezoelectric ceramic materials, piezoelectric transducers and other products.

Please insure the component is thoroughly evaluated in your application circuit.

In case that the component is not mentioned in our statement, please contact your Murata representative for details.

# CONTENTS

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## Preface

<b>1</b>	<b>Introduction</b>	2
<b>2</b>	<b>Characteristics of Piezoelectric Ceramics (PIEZOTITE®)</b>	3
1.	Resonant Frequency and Vibration Mode	3
2.	Piezoelectric Material Constant Symbols	6
1	Frequency Constant N	6
2	Piezoelectric Constants d and g	6
3	Electromechanical Coupling Coefficient k	6
4	Mechanical Qm	6
5	Young's Modulus Y <sup>E</sup>	7
6	Poisson's Ratio σ <sup>E</sup>	7
7	Density ρ	7
8	Relative Dielectric Constant $\frac{\epsilon^r}{\epsilon_0}$	7
9	Curie Temperature T <sub>c</sub>	7
10	Coercive Field E <sub>c</sub>	7
<b>3</b>	<b>Murata's Piezoelectric Ceramics (PIEZOTITE®) Material</b>	8
1.	Characteristics of Typical Materials	8
2.	Features of PIEZOTITE® Materials	9
3.	Temperature Characteristics and Aging	9
<b>4</b>	<b>Murata's Piezoelectric Ceramic Resonators (PIEZOTITE®)</b>	10
1.	Shapes	10
2.	Standard Specification Models	10
3.	Notice	11
<b>5</b>	<b>Piezoelectric Ceramic (PIEZOTITE®) Applications</b>	12
	Piezoelectric Actuator	13
	Molded Underwater Transducer	17
	Ultrasonic Sensor	18
	Shock Sensor	26
	Knocking Sensor Elements	37
	Ultrasonic Bubble Sensor	38
	Electric Potential Sensor	39

## 1 Introduction

## 2 Characteristics of Piezoelectric Ceramics (PIEZOTITE®)

## 3 Murata's Piezoelectric Ceramics (PIEZOTITE®) Material

## 4 Murata's Piezoelectric Ceramics Resonators (PIEZOTITE®)

## 5 Piezoelectric Ceramic (PIEZOTITE®) Applications

# 1 Introduction

## 1. What are Piezoelectric Ceramics?

Piezoelectric ceramics are known for what are called the piezoelectric and reverse piezoelectric effects. The piezoelectric effect causes a crystal to produce an electrical potential when it is subjected to mechanical vibration. In contrast, the reverse piezoelectric effect causes the crystal to produce vibration when it is placed in an electric field. Of piezoelectric materials, Rochelle salt and quartz have long been known as single-crystal piezoelectric substances. However, these substances have had a relatively limited application range chiefly because of the poor crystal stability of Rochelle salt and the limited degree of freedom in the characteristics of quartz. Later, barium titanate ( $\text{BaTiO}_3$ ), a piezoelectric ceramic, was introduced for applications in ultrasonic transducers, mainly for fish finders. More recently, a lead titanate, lead zirconate system ( $\text{PbTiO}_3$ ,  $\text{PbZrO}_3$ ) appeared, which has electromechanical transformation efficiency and stability (including temperature

characteristics) far superior to existing substances. It has dramatically broadened the application range of piezoelectric ceramics. When compared with other piezoelectric substances, both  $\text{BaTiO}_3$  and  $\text{PbTiO}_3$ ,  $\text{PbZrO}_3$  have the following advantages:

### ■ Advantages

- ① High electromechanical transformation efficiency.
- ② High machinability.
- ③ A broad range of characteristics can be achieved with different material compositions (high degree of freedom in characteristics design).
- ④ High stability.
- ⑤ Suitable for mass production, and economical.

Murata, as a forerunner in the piezoelectric ceramic industry, offers an extensive range of products with piezoelectric applications.

## 2. Properties of Piezoelectric Ceramics

Piezoelectric ceramics are a type of multi-crystal dielectric with a high dielectric constant and are formed by two processes: first, high temperature firing. After firing, they have the characteristic crystal structure shown in Fig. 1 (a) but do not yet exhibit the piezoelectric property because the electrical dipoles within the crystals are oriented at random and the overall moment of the dipoles is canceled out. To make ceramics piezoelectric they must be polarized. A DC electric field of several kV/mm is applied to the piece of ceramic to align the internal electrical dipoles in a single orientation (see Fig. 1 (b)). Due to the strong dielectric property of the ceramic, the dipole moment remains unchanged after the electric field is removed, and the ceramic thus exhibits a strong piezoelectric property (see Fig. 1 (c)). When an AC signal is applied to a piezoelectric ceramic (piezoelectric transducer) in a frequency matching the specific elastic frequency of the ceramics (which depends on the shape of the material), the ceramic exhibits resonance. Since the ceramic has a very high electromechanical transforming efficiency at the point of

resonance, many applications use this resonance point. Also piezoelectric ceramics when molded in certain shapes have more than one point of resonance depending on vibration mode. In such a case, the vibration mode most suited for the application is selected.

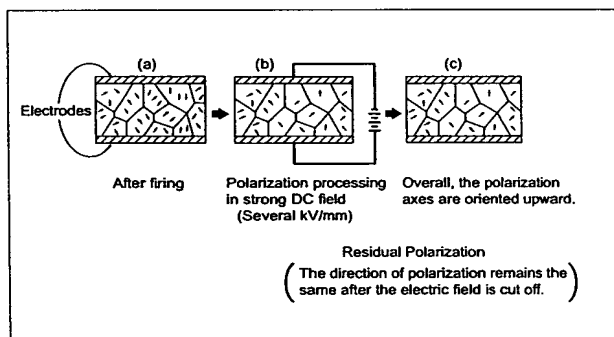


Fig. 1 Polarization Processing of Piezoelectric Ceramics

## 3. Application of Piezoelectric Ceramics

Product applications for piezoelectric ceramics include the following categories:

Murata has and is continuing to direct extensive research development efforts to the entire range of applications of piezoelectric ceramics listed in the right side. It is expected that the applications of piezoelectric ceramics will continue to extend into a broader range of industries as new piezoelectric materials are created.

This application manual concentrates on applications with mechanical power sources and sensors which are now finding broader applications.

### ■ Piezoelectric Applications

- ① Mechanical power sources (electrical-to-mechanical transducers):  
Piezoelectric actuators, piezoelectric fans, ultrasonic cleaners, etc.
- ② Sensors (mechanical-to-electrical transducers):  
Ultrasonic sensors, knocking sensors, shock sensors, acceleration sensors, etc.
- ③ Electronic circuit components (transducers):  
Ceramic filters, ceramic resonators, surface acoustic wave filters, microforks, etc.

## 2 Characteristics of Piezoelectric Ceramics (PIEZOTITE®)

For using piezoelectric ceramics, it is important to first have an adequate knowledge of the properties of different piezoelectric materials before choosing a suitable type for

a specific application. The following sections describe the major characteristic which need to be evaluated to determine the properties of piezoelectric ceramic materials.

### 1. Resonant Frequency and Vibration Mode

If an AC voltage of varying frequency is applied to a piezoelectric ceramic (piezoelectric transducer) of a certain shape, it can be seen that there is a specific frequency at which the ceramic produces a very strong vibration. This frequency is called the resonant frequency,  $f_r$ , and depends on the ceramic's specific elastic vibration (resonance) frequency, which is a function of the shape of the material.

Piezoelectric ceramics have various vibration modes (resonant modes) which depend on their shape, orientation of polarization, and the direction of the electric field. Each of these vibration modes have unique

resonant frequencies and piezoelectric characteristics. Fig. 2 shows typical vibration modes in relation to the shapes of ceramic materials, the resonant frequency in each vibration mode, and the material constant symbols. In Fig. 2, the piezoelectric material constant symbols have the following meanings:

- N** : Frequency Constant (described in Section 1).
- d** : Piezoelectric Distortion Constant (described in Section 2).
- g** : Voltage Output Constant (described in Section 2).
- k** : Electromechanical Coupling Coefficient (described in Section 3).
- $Y^E$**  : Young's Modulus (described in Section 5).
- $\epsilon^T$**  : Dielectric Constant (described in Section 8).

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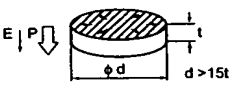
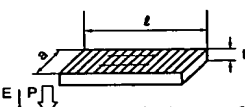
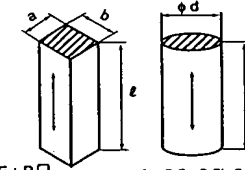
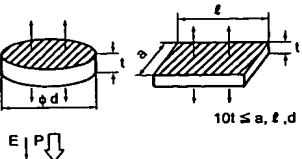
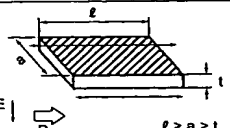
Vibration Mode	Shape/Vibration Mode	Resonant Frequency ( $f_r$ )	Material Constant Symbol					
			k	d	g	$Y^E$	$\epsilon^T$	N
Radial Mode	 <p>P : Direction of polarization E : Direction of electric field Thin disk with radial vibration mode. Polarization is oriented along the thickness of the disk.</p>	$\frac{N_p}{d}$	$k_p$	$d_{31}$	$g_{31}$	$Y_{11}^E$	$\epsilon_{33}^T$	$N_p$
Length Mode	 <p>Thin rectangular plate, with the direction of vibration orthogonal to the polarization axis and with a single point of resonance.</p>	$\frac{N_{31}}{l}$	$k_{31}$	$d_{31}$	$g_{31}$	$Y_{11}^E$	$\epsilon_{33}^T$	$N_{31}$
Longitudinal Mode	 <p>Square and cylindrical columns. Vibration is oriented along the direction of polarization. Only a single point of resonance.</p>	$\frac{N_{33}}{l}$	$k_{33}$	$d_{33}$	$g_{33}$	$Y_{33}^E$	$\epsilon_{33}^T$	$N_{33}$
Thickness Mode	 <p>Disk and rectangular plates which are thin compared to their surface areas. They have multiple points of resonance in longitudinal vibration mode.</p>	$\frac{N_t}{t}$	$k_t$	$d_{33}$	$g_{33}$	$Y_{33}^E$	$\epsilon_{33}^T$	$N_t$
Shear Mode	 <p>Disk or rectangular plates, with the electric field orthogonal to the direction of polarization, causing a shear vibration along the surface.</p>	$\frac{N_{15}}{t}$	$k_{15}$	$d_{15}$	$g_{15}$	$Y_{44}^E$	$\epsilon_{11}^T$	$N_{15}$

Fig. 2 Typical Vibration Modes, Resonant Frequencies, and Material Constant Symbols of Piezoelectric Ceramics

## 2 Characteristics of Piezoelectric Ceramics (PIEZOTITE®)

When a piezoelectric material is subjected to stress  $T$ , it produces polarization  $P$  which is a linear function of  $T$ :  $P=dT$  ( $d$ : piezoelectric strain constant). This effect is called the normal piezoelectric effect. In contrast, when a piezoelectric substance has an electric field  $E$  applied across its electrodes, it produces distortion  $S$  which is a linear function of the electric field:  $S=dE$ . This effect is called the reverse piezoelectric effect. For an elastic material, the relationship of distortion  $S$  to the stress  $T$  is given by  $S=s^E T$  ( $s^E$ : compliance); for a dielectric substance, the relationship of electrical displacement  $D$  with electric field strength  $E$  is given by  $D=\epsilon E$ . For a piezoelectric ceramic, these relationships are given by the following equations, both being associated with piezoelectric strain constants:

$$\left. \begin{aligned} S_i &= s_{ij}^E T_j + d_{im} E_m \\ D_h &= d_{hj} T_j + \epsilon_{nm}^T E_n \end{aligned} \right\} \dots\dots (1)$$

$$(m, n = 1, 2, 3; i, j = 1, 2, \dots\dots, 6)$$

These equations are called the basic piezoelectric equations (type d), where the electric field  $E$  and electrical displacement  $D$  are represented in vector magnitudes; whereas stress  $T$  and distortion  $S$  are given in symmetrical tensile magnitudes. When the symmetry of the crystals is taken into account, Eq. (1) is simplified because some constants in the equations are nullified and some other constants become equal to a third set of constants.

With piezoelectric ceramics, when the polarization axis is placed along the  $z$  (3) axis and two arbitrary orthogonal axes (which are also orthogonal to the  $z$  axis and assumed to be the  $x$  (1) and  $y$  (2) axis), the crystal structure of the ceramic can be represented in the same way as that of 6mm crystals, in which case the only independent non-zero coefficients are the following ten constants:

$$s_{11}^E \left( \frac{1}{Y_{11}^E} \right), s_{12}^E \left( \frac{1}{Y_{12}^E} \right), s_{13}^E \left( \frac{1}{Y_{13}^E} \right), s_{33}^E \left( \frac{1}{Y_{33}^E} \right), s_{44}^E \left( \frac{1}{Y_{44}^E} \right),$$

$$d_{31}, d_{33}, d_{15}, \epsilon_{11}^T, \epsilon_{33}^T.$$

For example, the basic piezoelectric equations for longitudinal vibration of a rectangular ceramic strip is given by the following equations:

$$\left. \begin{aligned} S_1 &= s_{11}^E T_1 + d_{31} E_3 \\ D_3 &= d_{31} T_1 + \epsilon_{33}^T E_3 \end{aligned} \right\} \dots\dots (2)$$

A piezoelectric ceramic transducer can be represented by an equivalent circuit which is derived from the basic piezoelectric equations representing its vibration mode. The circuit is called Maison's equivalent circuit. More generally, the equivalent circuit, as shown in Fig. 3, may be used to represent a piezoelectric ceramic. In this equivalent circuit, the serial resonant frequency  $f_s$ , and parallel resonant frequency  $f_p$  are given by the following equations:

$$\left. \begin{aligned} f_s &= \frac{1}{2\pi\sqrt{L_1 C_1}} \\ f_p &= \frac{1}{2\pi\sqrt{L_1 \cdot \frac{C_1 C_0}{C_1 + C_0}}} \end{aligned} \right\} \dots\dots (3)$$

Constants  $f_s$  and  $f_p$  are necessary to determine the electro-mechanical coupling coefficient  $k$ .

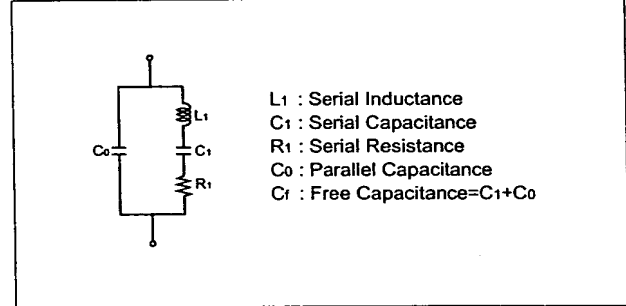


Fig. 3 Equivalent Circuit for Piezoelectric Ceramic Transducer

Strictly speaking, the resonant frequency can be defined in the following three ways:

- (1) Serial resonant frequency  $f_s$  of the equivalent serial circuit for a piezoelectric ceramic transducer.
- (2) Lower resonance frequency  $f_r$ , the lower of the two frequencies, where the cross-electrode admittance or impedance of the piezoelectric ceramic transducer is in the null phase.
- (3) Maximum admittance frequency  $f_m$  where the cross-electrode admittance of the piezoelectric ceramic transducer is maximized (impedance minimized).

However, the differences between the three frequencies,  $f_s$ ,  $f_r$ , and  $f_m$ , is so small that it is negligible. In actual cases, therefore, when we measure frequency  $f_m$ , it can be called resonant frequency  $f_r$ . Also, the minimum admittance frequency  $f_n$  may be called antiresonant frequency  $f_a$ . The resonant frequency  $f_r$  can be measured with either of the following two circuits:

## Characteristics of Piezoelectric Ceramics (PIEZOTITE®) 2

### ■ Measuring Method Using Constant Voltage Circuit

The  $f_r$  measuring circuit using a constant voltage source is shown in Fig. 4.

The oscillator Osc and input resistors  $R_1$  and  $R_2$  are used to apply a constant voltage signal to the piezoelectric ceramic transducer. The current passing through the transducer is measured across output resistor  $R_2$ . If the transducer's impedance is much greater than  $R_2$ , the voltmeter reading is proportional to the transducer's admittance. The frequency where the voltmeter reading is maximized is the resonant frequency  $f_r$ , and the frequency where the reading is minimized is the antiresonant frequency  $f_a$ .

Variable resistor  $R_v$  is used to determine the resonant resistance  $R_1$ , which is needed to calculate the mechanical  $Q_m$ .

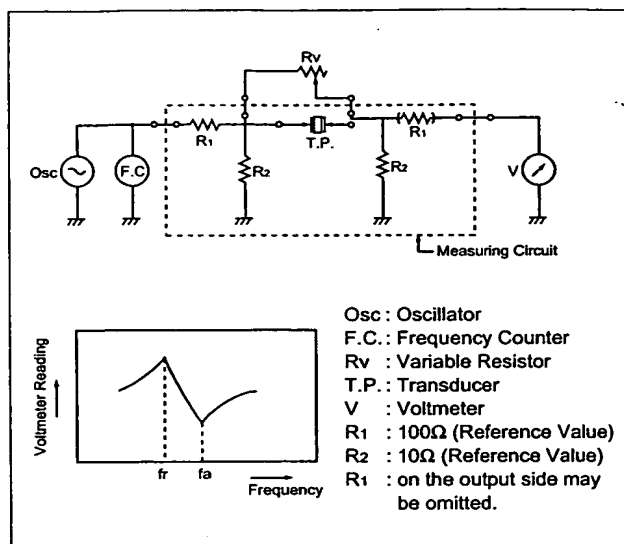


Fig. 4 Resonant Frequency Measuring Method Using Constant Voltage Circuit

### ■ Measuring Method Using Constant Current Circuit

The  $f_r$  measuring circuit using a constant current source is shown in Fig. 5. Resistor  $R_3$  regulates the current passing through the piezoelectric ceramic transducer. If  $R_3$  is much greater than the transducer's impedance, the voltmeter reading is proportional to the transducer's impedance. The frequency where the voltmeter reading is minimized is the resonant frequency  $f_r$ , and the frequency where the reading is maximized is the antiresonant frequency  $f_a$ .

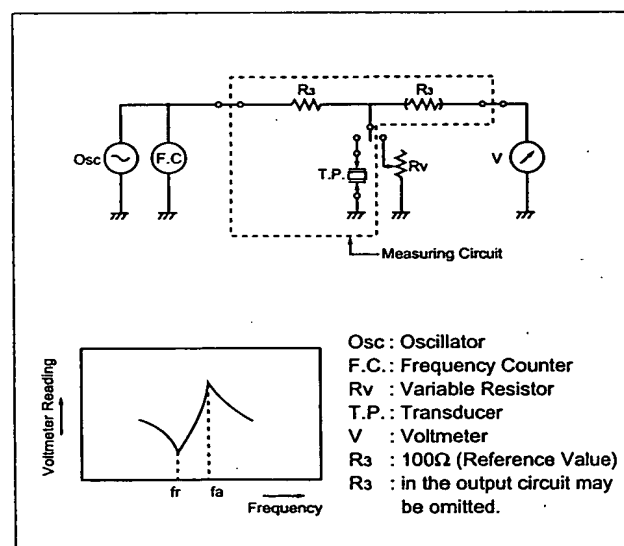


Fig. 5 Resonant Frequency Measuring Circuit Using Constant Current Circuit

## 2 Characteristics of Piezoelectric Ceramics (PIEZOTITE®)

### 2. Piezoelectric Material Constant Symbols

#### 1 Frequency Constant N

The velocity of sound that propagates through a piezoelectric ceramic has a specific value in each vibration mode when the resonance of other vibration modes is not in the vicinity. For a piezoelectric ceramic with a certain shape, the relationship of wavelength  $\lambda$  of a vibration with propagation length  $\ell$  at the resonant point is given by equation (4). Because the sound velocity is constant, we obtain the following equations (5) and (6) :

$$\frac{\lambda}{2} = \ell \quad \text{..... (4)}$$

$$v = fr \cdot \lambda \quad \text{..... (5)}$$

$$fr \cdot \ell = \frac{v}{2} = N \text{ (Hz} \cdot \text{m)} \quad \text{..... (6)}$$

where N is the frequency constant. The frequency constant depends on the vibration mode. The resonant frequency may also be determined by the equation,  $fr = N / \ell$  as shown in Fig. 2.

#### 2 Piezoelectric Constants d and g

##### ① Piezoelectric Distortion Constant d

Piezoelectric distortion constant is the distortion resulting from the application of an electric field of uniform strength with no stress. It is given by equation (7) :

$$d = k \sqrt{\frac{\epsilon^T}{Y^E}} \text{ (m/V)} \quad \text{..... (7)}$$

where  $\epsilon^T$  : Dielectric constant

$Y^E$  : Young's modulus (N/m<sup>2</sup>)

k : Electromechanical coupling coefficient

$$d_{31} = k_{31} \sqrt{\frac{\epsilon_{33}^T}{Y_{11}^E}}, d_{33} = k_{33} \sqrt{\frac{\epsilon_{33}^T}{Y_{33}^E}}, d_{15} = k_{15} \sqrt{\frac{\epsilon_{11}^T}{Y_{55}^E}} \quad \text{..... (8)}$$

##### ② Voltage Output Coefficient g

Voltage output coefficient refers to the field strength which results from a uniform stress applied under no electrical displacement. It is given by equation (9) :

$$g = \frac{d}{\epsilon^T} \text{ (V} \cdot \text{m/N)} \quad \text{..... (9)}$$

$$g_{31} = \frac{d_{31}}{\epsilon_{33}^T}, g_{33} = \frac{d_{33}}{\epsilon_{33}^T}, g_{15} = \frac{d_{15}}{\epsilon_{11}^T} \quad \text{..... (10)}$$

Constants d and g depend on the vibration mode, and the constants in each vibration mode are given by the subscripted symbols shown in Fig. 2.

Displacements generated under an electric voltage or a voltage generated under force can be determined by constants d and g. For example, the displacement  $\Delta \ell$  caused by voltage V applied across the electrodes in the lengthwise vibration mode is given by :

$$\frac{\Delta \ell}{\ell} = d_{31} \cdot \frac{V}{t} \quad \text{..... (11)}$$

Conversely, the voltage V caused by force F applied along the direction of vibration is given by :

$$V = g_{31} \cdot \frac{1}{a} F \quad \text{..... (12)}$$

#### 3 Electromechanical Coupling Coefficient k

The electromechanical coupling coefficient is a constant representing the piezoelectric efficiency of a piezoelectric ceramic. More specifically, it represents the efficiency of converting electrical energy (applied across the electrodes of a piezoelectric ceramic) into mechanical energy, and it is defined as the root mean square of the energy accumulated within the crystal in a mechanical form. This accumulated energy reflects the total electrical input.

$$\text{Electromechanical Coupling Coefficient} = \sqrt{\frac{\text{Accumulated Mechanical Energy}}{\text{Supplied Electrical Energy}}}$$

The electromechanical coupling coefficient depends on the vibration mode, as shown in Fig. 2. It is determined by the following equations using the resonant frequency  $fr$ , anti-resonant frequency  $fa$ , and their difference  $\Delta f = fa - fr$ .

##### ① Radial Vibration of Disk Transducer

$$\frac{kp^2}{1 - kp^2} = \frac{(1 - \sigma^E) J_1 \{ \psi_1 (1 + \Delta f / fr) \} \cdot \psi_1 (1 + \Delta f / fr) J_0 \{ \psi_1 (1 + \Delta f / fr) \}}{(1 + \sigma^E) J \{ \psi_1 (1 + \Delta f / fr) \}} \quad \text{..... (13)}$$

where  $J_0, J_1$  : Type 1 vessel functions of the 0th and 1st dimensions

$\sigma^E$  : Poisson's ratio

$\psi_1$  : Lowest dimension of positive root of  $(1 - \sigma^E) J_1(\psi) = \psi J_0(\psi)$

If  $kr$  is relatively small, equation (13) may be approximated as follows :

$$kp^2 = 2.529 \cdot \frac{\Delta f}{fr} \quad \text{..... (14)}$$

##### ② Lengthwise Vibration of Rectangular Plate Transducer

$$\frac{k_{31}^2}{1 - k_{31}^2} = -\frac{\pi}{2} \cdot \frac{fa}{fr} \cot \left( \frac{\pi}{2} \cdot \frac{fa}{fr} \right) \quad \text{..... (15)}$$

##### ③ Longitudinal Vibration of Cylinder Transducer

$$k_{33}^2 = \frac{\pi}{2} \cdot \frac{fr}{fa} \cot \left( \frac{\pi}{2} \cdot \frac{fr}{fa} \right) \quad \text{..... (16)}$$

##### ④ Vibration Along Thickness of Disk Transducer

$$k_t^2 = \frac{\pi}{2} \cdot \frac{fr}{fa} \cot \left( \frac{\pi}{2} \cdot \frac{fr}{fa} \right) \quad \text{..... (17)}$$

##### ⑤ Shear Vibration of Rectangular Plate Transducer

$$k_{15}^2 = \frac{\pi}{2} \cdot \frac{fr}{fa} \cot \left( \frac{\pi}{2} \cdot \frac{fr}{fa} \right) \quad \text{..... (18)}$$

#### 4 Mechanical Qm

Mechanical Qm gives the "steepness" of resonance of a mechanical vibration at and around the resonant frequency. It is given by the following equation :

$$Qm = \frac{1}{2 \pi fr R_1 C_f} = \frac{1}{2 \pi fr R_1 C_f \left\{ 1 - \left( \frac{fr}{fa} \right)^2 \right\}} \quad \text{..... (19)}$$

where  $R_1$  : Resonant resistance

$C_f$  : Free capacitance across electrodes



## Characteristics of Piezoelectric Ceramics (PIEZOTITE®) 2

### 5 Young's Modulus $Y^E$

When stress  $T$  is applied to an elastic body within the proportional elastic range, strain  $S$  is given by the following formula :

$$S = s^E T$$

$s^E$  is an elasticity constant (compliance), and Young's modulus is given as the inverse of compliance. For lengthwise vibrations shown in Fig. 3, for example, the Young's modulus is given by the following equation :

$$Y_{11}^E = (2\ell ft)^2 \cdot \rho = v^2 \cdot \rho \text{ (N/m}^2\text{)} \dots\dots\dots (20)$$

where  $\rho$  : Density (kg/m<sup>3</sup>)

$v$  : Sound velocity (m/s)

### 6 Poisson's Ratio $\sigma^E$

When a constant stress is applied to an elastic body within its proportional elastic range, Poisson's ratio is defined as follows :

$$\sigma^E = - \frac{\text{Distortion Rate Orthogonal to Stress}}{\text{Distortion Rate along Stress}}$$

### 7 Density $\rho$

Density can be determined from the volume and mass of any piezoelectric ceramic as follows :

$$\rho = \frac{m}{V} \text{ (kg/m}^3\text{)} \dots\dots\dots (21)$$

where  $m$  : Mass (kg)

$V$  : Volume (m<sup>3</sup>)

### 8 Relative Dielectric Constant $\frac{\epsilon^T}{\epsilon_0}$

Dielectric constant is an electrical displacement which results when a unity electric field is applied under no stress. It is given by the following formula :

$$D = \epsilon^T \cdot E$$

where  $E$  : Field strength

$D$  : Electrical displacement

$\epsilon^T$  : Dielectric constant

Dielectric constant  $\epsilon^T$  divided by the dielectric constant in a vacuum  $\epsilon_0$  ( $=8.854 \times 10^{-12}$  F/m) is called the relative dielectric constant. For the lengthwise vibration mode shown in Fig. 2, if the free capacitance across the electrodes at 1 kHz is assumed to be  $C_f$ , the relative dielectric constant for an electric field in the same direction of polarization is given by the equation :

$$\frac{\epsilon_{33}^T}{\epsilon_0} = \frac{C_f \cdot t}{\ell \cdot a \cdot \epsilon_0} \dots\dots\dots (22)$$

For the vibration along thickness shown in Fig. 2, if the free capacitance across the electrodes at 1 kHz is assumed to be  $C_f$ , the relative dielectric constant for an electric field orthogonal to the direction of polarization is given by this equation :

$$\frac{\epsilon_{11}^T}{\epsilon_0} = \frac{C_f \cdot t}{\ell \cdot a \cdot \epsilon_0} \dots\dots\dots (23)$$

### 9 Curie Temperature $T_c$

Curie temperature refers to the critical temperature at which crystals in the piezoelectric ceramic lose their spontaneous polarization and hence their piezoelectric property. It is defined as the temperature at which the dielectric constant is maximized when the temperature is increased.

### 10 Coercive Field $E_c$

Ferroelectric materials have a domain structure, as shown in Fig. 1. The dipole moment in each domain is oriented in the same direction and causes spontaneous polarization. If a varying electric field  $E$  is applied to it, the overall variation of polarization draws a hysteresis loop, as shown in Fig. 6. Once the material has an electric field applied to it, it does not return to the original domain structure when the electric field is removed, resulting in remanent polarization  $P_r$ . To cancel  $P_r$ , a certain strength of reverse electric field must be applied. The field strength  $E_c$  required to cancel the remanent polarization is called a coercive field.

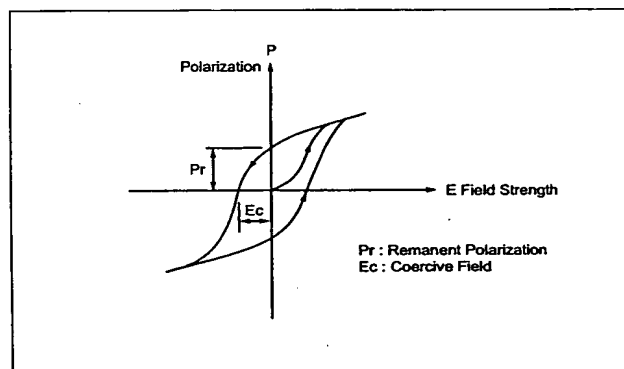


Fig. 6 Hysteresis Curve of a Ferroelectric Material

# 3 Murata's Piezoelectric Ceramics (PIEZOTITE®) Materials

## 1. Characteristics of Typical Materials

Table 1 shows the characteristics of typical Murata's piezo-electric ceramic materials.

Item	Symbol (Unit)	P-3	P-5C	P-5E	P-6C	P-6E	P-6F	P-7	P-7B
Relative Dielectric Constant	$\epsilon_{11}/\epsilon_0$	—	1230	1490	760	1260	1670	1930	3200
	$\epsilon_{33}/\epsilon_0$	1070	1550	1510	800	1380	1780	2100	4720
Loss Coefficient	$\tan \delta$ (%)	0.5	0.3	0.4	1.0	1.4	1.2	1.4	2.2
Electro-mechanical Coupling Factor	$k_p$ Radial (%)	22	56	56	39	46	57	65	65
	$k_{31}$ Length (%)	15	32	32	21	26	32	38	36
	$k_{33}$ Longitudinal (%)	44	54	62	50	60	65	71	68
	$k_t$ Thickness (%)	36	42	45	43	44	48	51	47
	$k_{15}$ Shear (%)	—	50	60	47	53	61	66	57
Piezoelectric Constant	$d_{31}$ ( $10^{-12}\text{m/V}$ )	-44	-131	-131	-3	-94	-148	-207	-303
	$d_{33}$ ( $10^{-12}\text{m/V}$ )	133	225	271	135	235	311	410	603
	$d_{15}$ ( $10^{-12}\text{m/V}$ )	—	294	400	196	309	431	550	592
	$g_{31}$ ( $10^{-3}\text{V}\cdot\text{m/N}$ )	-5	-10	-10	-8	-8	-9	-11	-7
	$g_{33}$ ( $10^{-3}\text{V}\cdot\text{m/N}$ )	14	16	20	19	19	20	22	14
	$g_{15}$ ( $10^{-3}\text{V}\cdot\text{m/N}$ )	—	27	30	29	28	29	32	21
Frequency Constant	$N_p$ Radial (%)	3140	1920	2250	2520	2410	2210	2050	1960
	$N_{31}$ Length (%)	2270	1580	1610	1850	1730	1540	1430	1370
	$N_{33}$ Longitudinal (%)	2210	1670	1550	1820	1670	1540	1400	1350
	$N_t$ Thickness (%)	2590	2180	2060	2130	2110	2060	2000	1970
	$N_{15}$ Shear (%)	—	1020	1010	1150	1080	1000	930	930
Mechanical Q	$Q_m$	720	2070	970	680	410	110	80	70
Elastic constant	$S_{11}^E$ ( $10^{-12}\text{m}^2/\text{N}$ )	8.7	12.6	12.4	9.4	11.1	13.4	15.8	16.7
	$S_{12}^E$ ( $10^{-12}\text{m}^2/\text{N}$ )	-2.6	-4.7	-4.1	-3.0	-3.6	-4.8	-5.7	-5.9
	$S_{13}^E$ ( $10^{-12}\text{m}^2/\text{N}$ )	-2.9	-5.3	-5.2	-3.0	-4.3	-5.4	-7.0	-7.5
	$S_{33}^E$ ( $10^{-12}\text{m}^2/\text{N}$ )	9.6	12.8	14.3	10.3	12.7	14.5	18.1	18.8
	$S_{44}^E$ ( $10^{-12}\text{m}^2/\text{N}$ )	—	31.6	34.0	25.6	30.0	34.2	40.6	38.8
	$S_{66}^E$ ( $10^{-12}\text{m}^2/\text{N}$ )	22.7	34.6	33.0	24.8	29.3	36.5	43.0	45.4
	$Y_{11}^E$ ( $10^{10}\text{N/m}^2$ )	11.5	8.0	8.1	10.7	9.0	7.5	6.3	6.7
Poisson's Ratio	$\sigma^E$	0.30	0.37	0.33	0.32	0.33	0.36	0.36	0.36
Density	$\rho$ ( $10^3\text{kg/m}^3$ )	5.6	8.0	7.8	7.7	7.6	7.9	7.8	8.0
Temperature Coefficient	TK(fr) (ppm/°C)	—	324	115	10	35	38	59	336
	TK(Cf) (ppm/°C)	—	1500	3500	2500	3000	—	4500	13500
Curie Temperature	$T_c$ (°C)	120	360	280	320	270	280	300	180
Linear Expansion Ratio	$\alpha$ ( $10^{-6}/^\circ\text{C}$ )	5	2	4	2	3	4	2	2
Bending Strength	$\tau$ ( $10^6\text{N/m}^2$ )	113	101	113	125	116	103	99	85
Compressive Strength	$K_{1c}$ ( $10^6\text{N/m}^{1.5}$ )	—	0.7	1.1	1.3	1.2	0.9	0.8	0.9
Applications		Fish finders sonars	Ultrasonic cleaners Actuators for high power	Knock sensors	Sensors			Ultrasonic sensors Pickups Actuators Acoustic	Actuators Acoustics

Note : This table shows typical values measured on standard test piece.  $Q_m$ , TK (fr) and TK (Cf) are measured for radial vibration mode.

Table 1 Characteristics of Murata's Typical Piezoelectric Ceramics (PIEZOTITE®)

## Murata's Piezoelectric Ceramics (PIEZOTITE®) Materials 3

### 2. Features of PIEZOTITE® Materials

Table 2 shows the features of PIEZOTITE® materials.  
Murata's piezoelectric ceramics include two types : barium titanate (BaTiO<sub>3</sub>) and lead zirconate titanate

(PbTiO<sub>3</sub>, PbZrO<sub>3</sub>) Materials using lead zirconate titanate are available with different properties suitable for different applications.

Type	Type Number	Features
Barium Titanate	P-3	The major constituent of P-3 is barium titanate, with titanate additives to improve the characteristics at room temperature. While it has a lower electromechanical coupling coefficient and Curie temperature compared to Lead Zirconate Titanate, it is practical in underwater applications and has the advantage of economy. With these features, P-3 is best suited for use in fish finders or sonar.
Lead Zirconate Titanate	P-5E	Featuring a large electromechanical-coupling coefficient, mechanical Qm and minimal aging, P-5 is widely used for ultrasonic cleaners, high-power ultrasonic transducers, and other acoustic power applications.
	P-6C	Features superior temperature characteristics of resonant frequency and minimal aging. P-6 is often used in ceramic filters, ceramic resonators requiring high stability.
	P-7	Features large electromechanical coupling coefficient, constant d and small mechanical Qm. P-7 has applications in piezoelectric buzzers, ultrasonic sensors, and other applications requiring non-resonance or broad bandwidth.

Table 2 Features of Piezoelectric Ceramics

### 3. Temperature Characteristics and Aging

Fig. 7 shows examples of temperature characteristics of various materials.

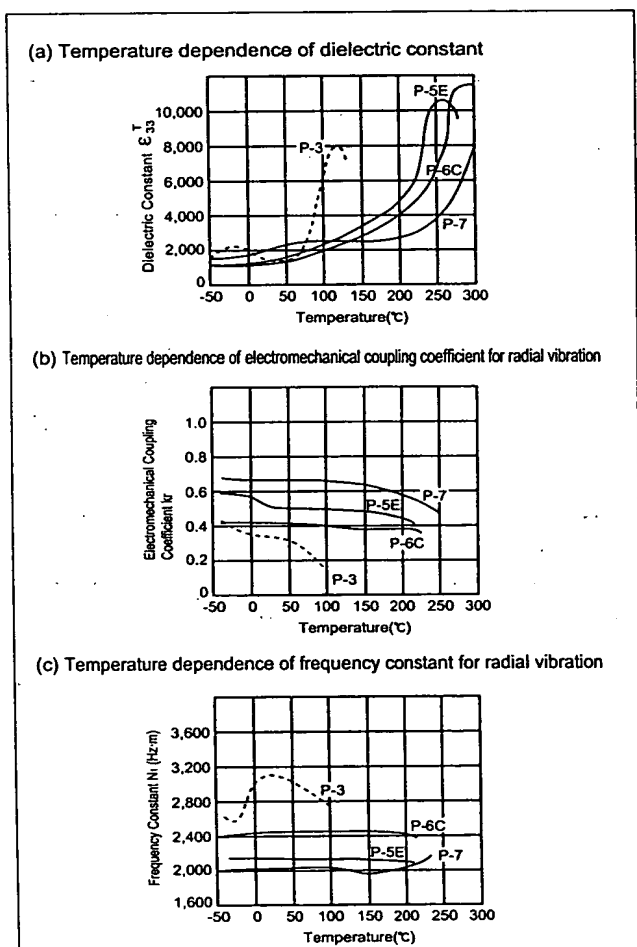


Fig. 7 Temperature Characteristics of Various Materials

Fig. 8 shows examples of aging characteristics of various materials. These examples show small aging characteristics.

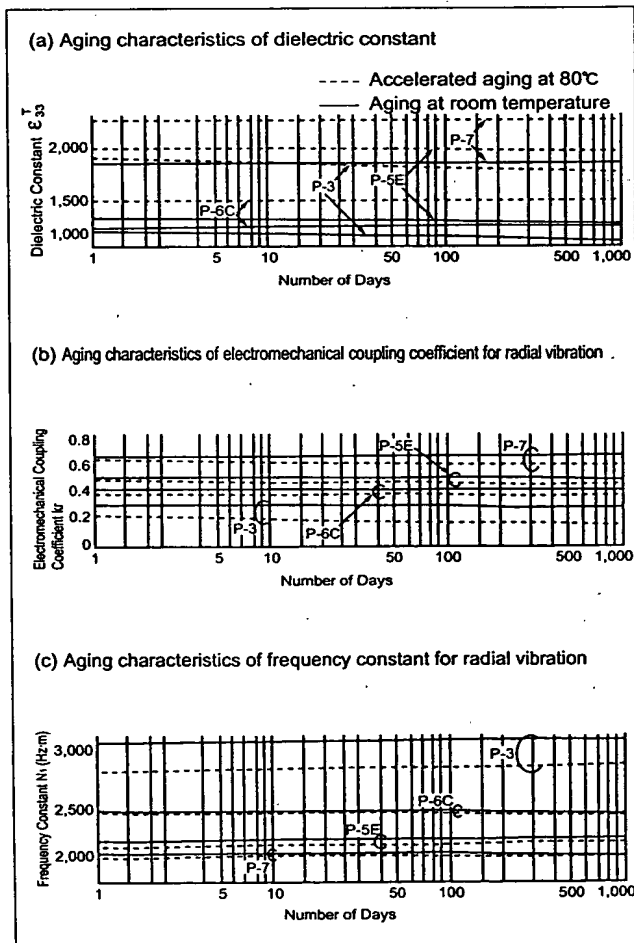
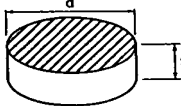
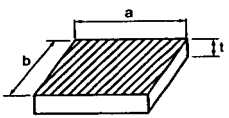
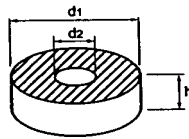


Fig. 8 Aging Characteristics of Various Materials

# 4 Murata's Piezoelectric Ceramics Resonators (PIEZOTITE®)

## 1. Shapes

PIEZOTITE® by Murata is available in various forms as shown in table 3.

Shape	Diagram	Vibration Mode	Part Numbering (Ex.)
Disk		Radial Thickness	<div> <div>7</div> <div>D</div> <div>-15</div> <div>-5400</div> </div> <div> <div>1</div> <div>2</div> <div>3</div> <div>4</div> </div> <div> <div>1</div> <div>Indicates material P-7.</div> </div> <div> <div>2</div> <div>Indicates disk cylinder.</div> </div> <div> <div>3</div> <div>Diameter d(mm)</div> </div> <div> <div>4</div> <div>Resonant frequency (thickness mode) (kHz)</div> </div>
Rectangular Plate		Thickness Length	<div> <div>7</div> <div>R</div> <div>-34</div> <div>-23</div> <div>-6700</div> <div>-1</div> </div> <div> <div>1</div> <div>2</div> <div>3</div> <div>4</div> <div>5</div> <div>6</div> </div> <div> <div>1</div> <div>Indicates material P-7.</div> </div> <div> <div>2</div> <div>Indicates rectangular plate or pillar.</div> </div> <div> <div>3</div> <div>Length a (mm)</div> </div> <div> <div>4</div> <div>Width b (mm)</div> </div> <div> <div>5</div> <div>Resonant frequency (thickness mode) (kHz)</div> </div> <div> <div>6</div> <div>Product ID</div> </div>
Ring		Thickness	<div> <div>6C</div> <div>C</div> <div>-10</div> <div>-3R9</div> <div>-1000</div> </div> <div> <div>1</div> <div>2</div> <div>3</div> <div>4</div> <div>5</div> </div> <div> <div>1</div> <div>Indicates material P-6C.</div> </div> <div> <div>2</div> <div>Indicates ring.</div> </div> <div> <div>3</div> <div>Outer diameter d1 (mm)</div> </div> <div> <div>4</div> <div>Inner diameter d2 (mm)</div> </div> <div> <div>5</div> <div>Resonant frequency (thickness mode) (kHz)</div> </div>

The capital letter "R" expresses significant digits.

Fig. 9 Shapes of Murata's Piezoelectric Ceramics PIEZOTITE®

## 2. Standard Specification Models

Table 3 shows standard specifications of PIEZOTITE® models.

	Part Number	Dimensions (mm)	Resonant Frequency (kHz)	Coupling Coefficient (%)	Capacitance (pF)
Disks	7D-10-9000-2	ø10X0.2t	200 (Radial mode)	55 (kp)	5200
	7D-15-5400	ø15X0.4t	137 (Radial mode)	55 (kp)	7200
	7D-25-1600	ø25.5X1.27t	80 (Radial mode)	45 (kp)	6300
Rectangular Plates	7R-34-23-2500	33.3LX22.8WX0.8t	68 (Length mode)	50 (kp)	16000
	7R-34-23-4000-1	33.3LX22.8WX0.5t	42 (Length mode)	20 (kp)	26000
	7R-34-23-6700	32.8LX22.3WX0.3t	42 (Length mode)	20 (kp)	42000
Rings	6CC-21-15-700	ø21.1Xø15X2.85t	66 (Radial mode)	18 (kp)	450
	6CC-10-3R9-1000	ø10Xø3.9X2.1t	180 (Radial mode)	20 (kp)	230

Table 3 Standard Specifications of PIEZOTITE® Models

## Murata's Piezoelectric Ceramics Resonators (PIEZOTITE®)

4

### 3. Notice

Do not touch the component with bare hand because electrode may damaged.

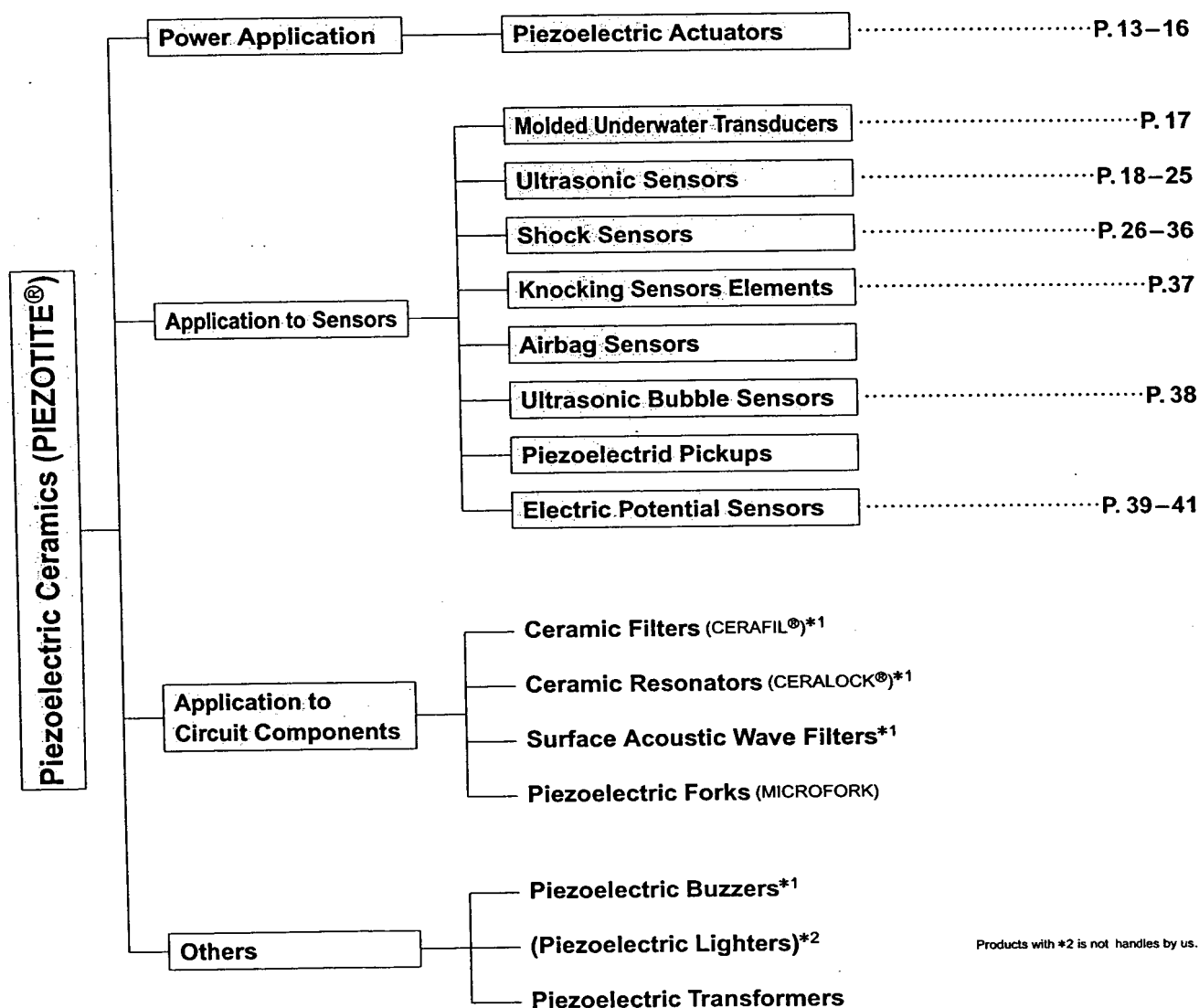
4

## 5 Piezoelectric Ceramic (PIEZOTITE®) Applications

Piezoelectric ceramics transform electrical energy into mechanical energy and vice versa. Fig. 10 shows our PIEZOTITE® in applications which utilize this basic function of piezoelectric ceramics as an electrical-mechanical energy transducer.

In addition to the current line of products, Fig. 10 also lists some prototypes still under development (\*1). Please

consult us concerning custom specifications and production of these new products. The application products are shown in □, which are explained details in the following pages. For other products not shown in Fig. 10, please contact us. Items marked with an asterisk (\*1) in Fig. 10 are available with individual catalogs and application manuals. For more details, refer to those related materials.



Products with \*2 is not handles by us.

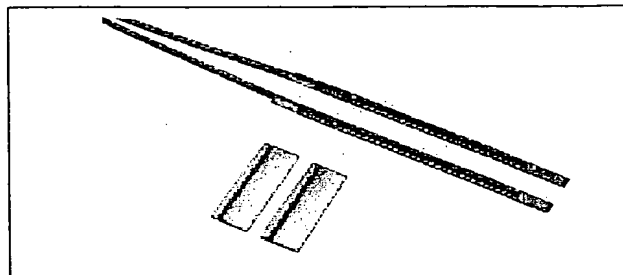
Fig. 10 Piezoelectric Ceramics (PIEZOTITE®) Applications

# Piezoelectric Ceramic Sensors (PIEZOTITE®)



## Piezoelectric Actuator

Exact displacement of 0.01μm to several hundreds μm can be obtained by controlling the applied voltage.  
Piezoelectric actuators are used in the tracking adjustment of VCR heads, focus adjustment of VCR cameras, shutter drives of cameras, ink-jet printers and braille cells.



Material	Piezoelectric Strain Constant		Corrective Coefficient	Elastic Constant (corrected value)		Coercive Field	Relative Dielectric Constant	Hysteresis
	$d_{31}(10^{-12}\text{m/V})$	$d_{33}(10^{-12}\text{m/V})$		$Y_{11}\text{E}(10^{10}\text{N/m}^2)$	$Y_{33}\text{E}(10^{10}\text{N/m}^2)$			
P-5E	131	271	0.06	7.5	8.0	1500	1510	3
P-7	207	410	1.08	5.5	5.5	800	2100	10
P-7B	303	603	3.89	5.0	5.5	500	4720	20

Hysteresis vary according to the applied voltage or shape (See Fig.2)

### ■ Notice

Please note that the component may be damaged if excess stress input voltage is applied. Please refer to the individual specification for the max. input voltage.

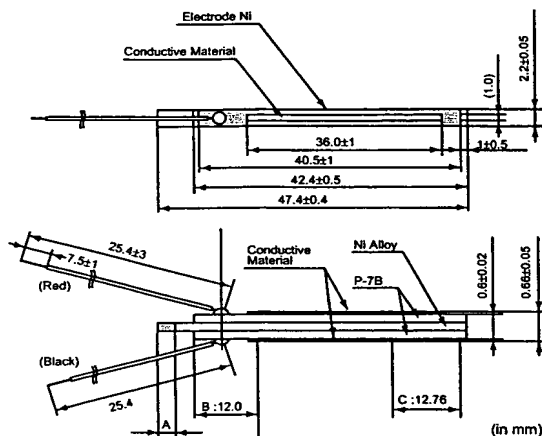
## Bimorph Type Actuator

### ■ Features

1. Large displacement achieved with low voltage.
2. Compact, low-cost design.
3. High response speed.

### ■ Applications

1. braille cells
2. shutter drives of cameras



- A : The length of pre-coating is more than 2.0mm from edge.
- There are protect-coating on the surface of ceramic. Above dimensions don't include coating thickness. The dimension included is as below.  
Point B : 0.7mm  
Point C : 0.74mm
- Lead wire : UL1571, AWG32

Part Number	Deflection	Input Voltage (V)	Blocked Force (mN)	Capacitance (nF)
PKF02C5	min. 1200 $\mu$ m (1300 $\mu$ m typ.) (at 200 V)	200 V max.	83.3 ±19.6mN (at 200 V)	5.7 ± 2.0nF (at 1 Vrms., 1 kHz)

### ■ Construction

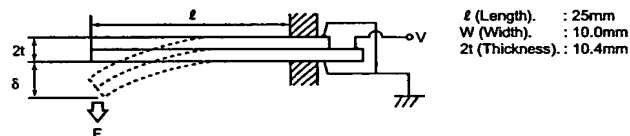


Fig. 1

(Mechanical strength can be increased with metal plate.)

### ■ Characteristics (Construction in Fig.1)

#### 1. Hysteresis

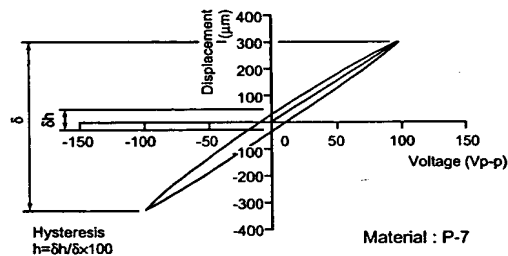


Fig. 2

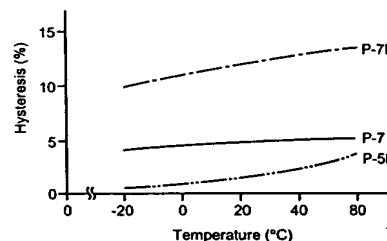


Fig.3



## 2. Displacement

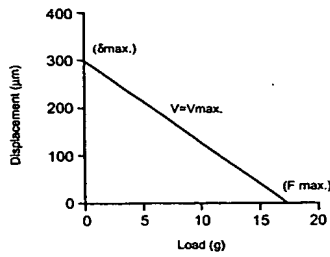


Fig. 4

Material : P-7  
Voltage : 100Vp-p  
Displacement :  $\delta \approx 3 \cdot D_{31} \cdot V \cdot \left(\frac{R}{2t}\right)^2$   
Generated force :  $F \approx \frac{3}{4} \cdot D_{31} \cdot V \cdot \left(\frac{2tW}{R}\right) \cdot Y_{11}$   
( $D_{31} = d_{31} + M \cdot V/2t$ )  
F : Load at 0 displacement  
Maximum allowable voltage :  $V_{max} \approx 0.7 \cdot E_c \cdot t$

$\approx 2,5 \mu m/V$  mit kleinen  
Maßen

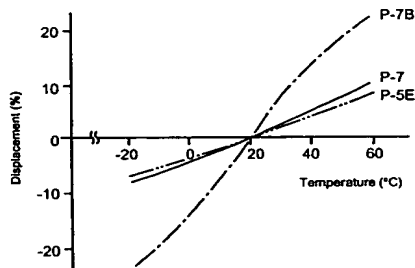


Fig. 5

## 3. Material · shape-Displacement

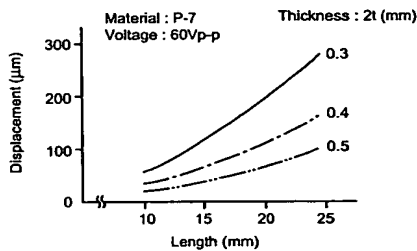


Fig. 6

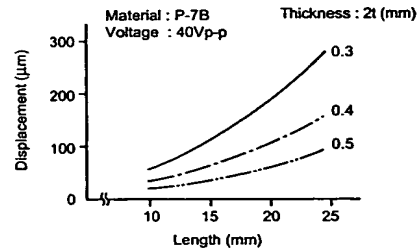


Fig. 7

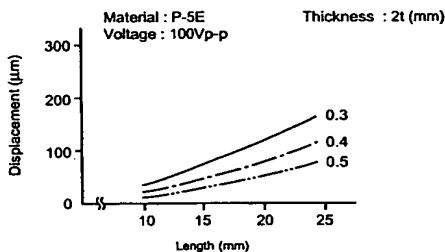


Fig. 8

### ■ Notice

Please avoid applying an excessive stress to the transducer because it might be damaged.

## Multilayer Type Actuator

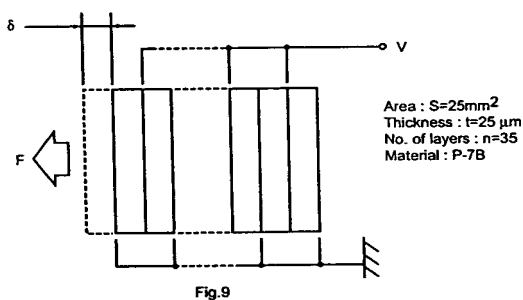
### ■ Features

1. Superior load-sustaining performance.
2. Precise micro-displacement.
3. High displacement response speed.

### ■ Applications

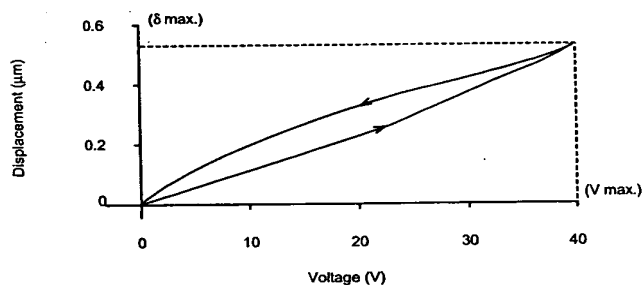
1. braille cells
2. shutter drives of cameras
3. Ink-jet Printer head
4. Location control for HDD MR-head

### ■ Construction

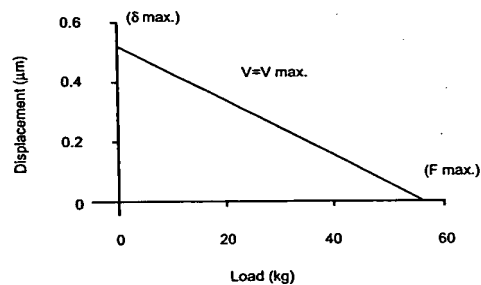


### ■ Characteristics

#### 1. Hysteresis



#### 2. Displacement



# Piezoelectric Ceramic Sensors (PIEZOTITE®)

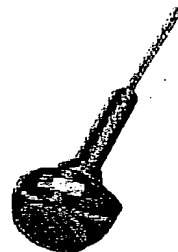
**muRata**

## Molded Underwater Transducer

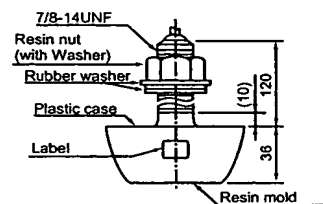
The molded underwater transducer is often used in fish finders and depth sounders. It emits an ultrasonic wave into the water so that the appropriate receiving device can detect the reflected wave in order to prove for fish or determine depth. Designed specifically for underwater use, this vibrator features not only high sensitivity but superior waterproof performance. The rugged design easily gives excellent performance even under high water pressure and waves.

### ■ Features

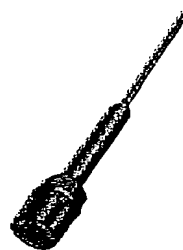
1. Unique mold technique using rubber, urethane, epoxy resin and other materials assures high sensitivity and dependability.
2. Many models are available for different driving frequencies, allowable input powers, and shapes.



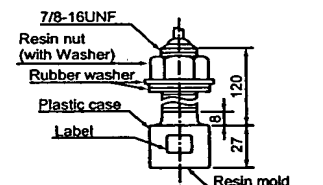
LF type  
(UT200LF8)



(in mm)



BA type  
(UT200BA8)



(in mm)

5

Part Number	Resonant Frequency (kHz)	Capacitance (pF)	Resonant Impedance (Ω)	Directivity (deg)	Allowable Input Power (W)
UT200BA8	200	1700	310 - 590	22	50
UT200LF8	200	2700	230 - 430	12	200

Wire length is 8 m.

Directivity: The degree when sound pressure level is 6 dB down compared with the value at 0 degree.

Allowable input power : Denotes the instantaneous input power applied to Molded underwater transducer driven underwater.

The driving duty ratio is assumed to be 1/200 (the values in the table above are guidelines)

### ■ Notice

1. Pay close attention to directional characteristics when mounting.
2. Please avoid applying DC-bias by connecting DC blocking capacitor or some other way because, otherwise, the component may be damaged.
3. Do not use in the air.

# Piezoelectric Ceramic Sensors (PIEZOTITE®)

**muRata**

## Ultrasonic Sensors

### Open Structure Type

#### ■ Features

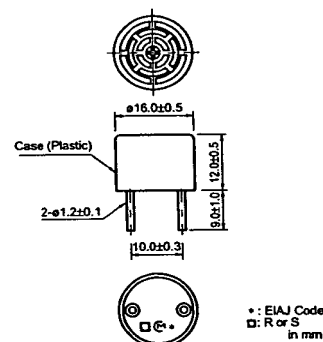
1. Compact and light weight.
2. High sensitivity and sound pressure.
3. Less power consumption.
4. High reliability.

#### ■ Applications

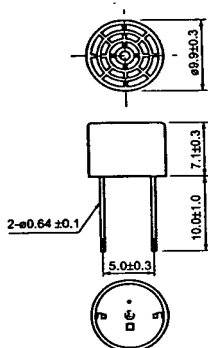
Burglar alarms, Range finders, Automatic doors, Remote control.



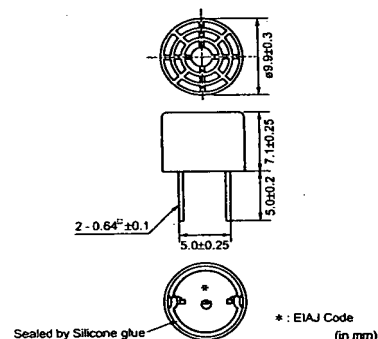
MA40B8R/S



MA40S4R/S



MA40S5



Part Number	Construction	Using Method	Nominal Freq. (kHz)	Overall Sensitivity (mVp-p)	Sensitivity (dB)	S.P.L. (dB)	Directivity (°)	Cap. (pF)	Operating Temp. Range (°C)	Detectable Range (m)	Resolution (mm)	Max. Input Voltage (Vp-p)
MA40B8R	Open struct.	Receiver	40	-	-63 typ. (0dB=10V/Pa)	-	50	2000	-30 to 85	0.2 to 6	9	-
MA40B8S	Open struct.	Transmitter	40	-	-	120 typ. (0dB=0.02mPa)	50	2000	-30 to 85	0.2 to 6	9	40 Continuous signal
MA40S4R	Open struct.	Receiver	40	-	-63 typ. (0dB=10V/Pa)	-	80	2550	-40 to 85	0.2 to 4	9	-
MA40S4S	Open struct.	Transmitter	40	-	-	120 typ. (0dB=0.02mPa)	80	2550	-40 to 85	0.2 to 4	9	20 Continuous signal
MA40S5	Open struct.	Dual Use	40	20 typ.	-	-	60 typ.	2550	-30 to 85	0.5 to 2	9	20 Pulse width 0.4ms Interval 100ms

Distance:30cm, Overall sensitivity:0dB=10Vp-p, Sensitivity:0dB=1Vrms/μbar, Sound pressure level:0dB=2x10<sup>-4</sup>μbar, 1μbar=0.1Pa

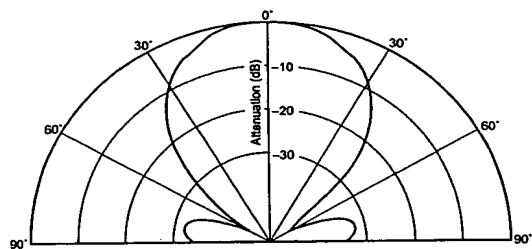
The sensor can be used in the operating temperature range.

Please refer to the individual specification for the temperature drift of Sensitivity/Sound pressure level or environmental characteristics in that temperature range.

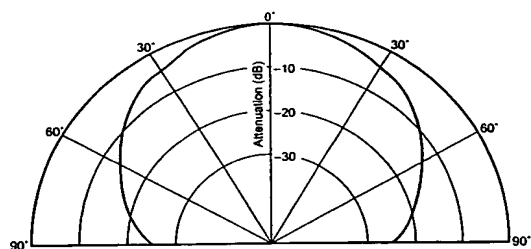
Directivity, detectable range and resolution are typical values. They can be changed by application circuit and fixing method of the sensor.

## ■ Directivity in Sensitivity

MA40B8R

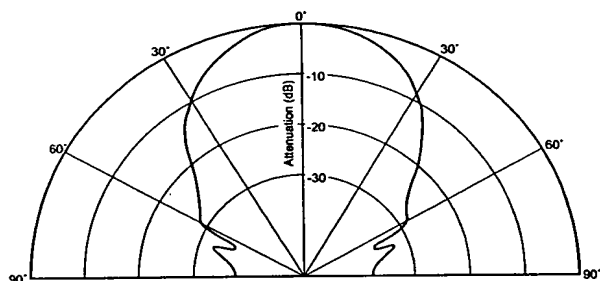


MA40S4R



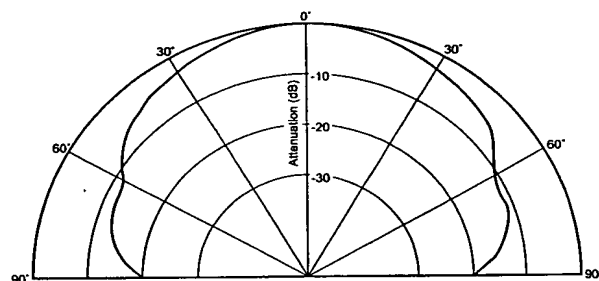
## ■ Directivity in S. P. L.

MA40B8S



## ■ Directivity in S. P. L.

MA40S4S

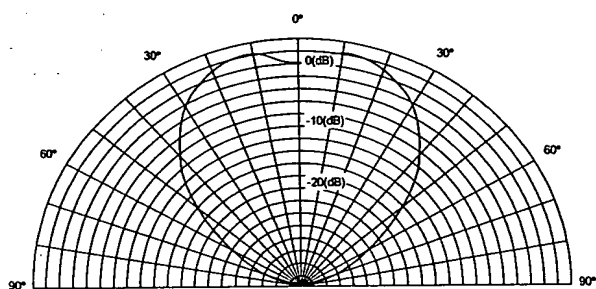


5

## ■ Directivity in Overall Sensitivity

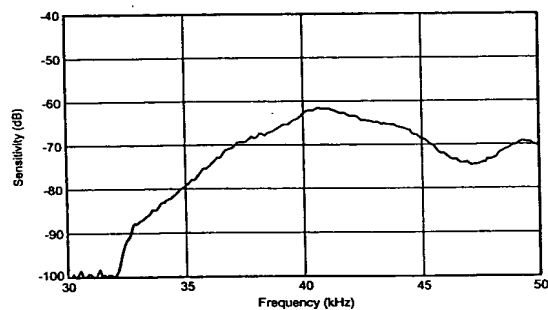
MA40S5

Bearn Pattern

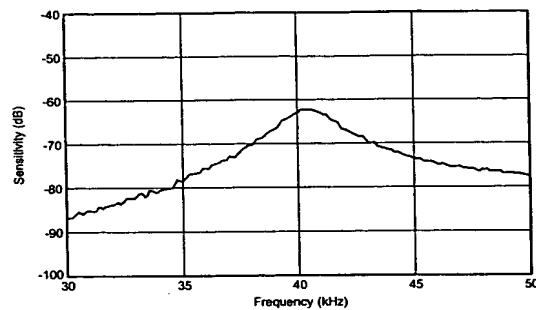


## ■ S. P. L. -Freq. Characteristics

MA40B8R

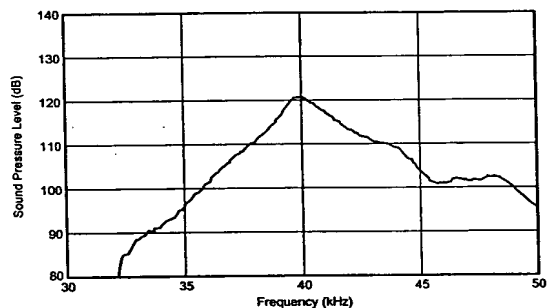


MA40S4R

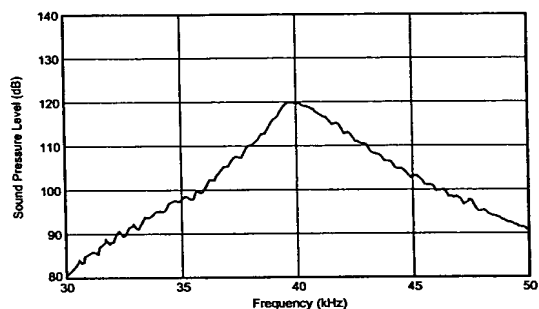


## ■ Sensitivity-Freq. Characteristics

MA40B8S



MA40S4S



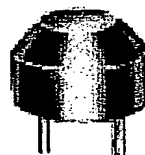
## Water Proof Type Symmetric Directivity

### ■ Features

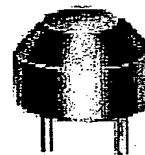
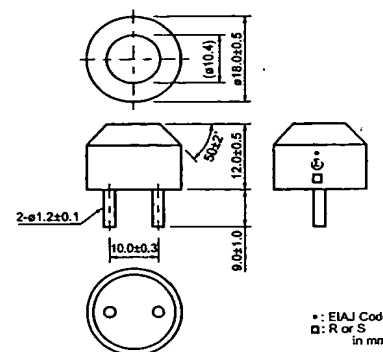
1. Compact and light weight.
2. High sensitivity and sound pressure.
3. Less power consumption.
4. High reliability.

### ■ Applications

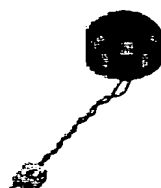
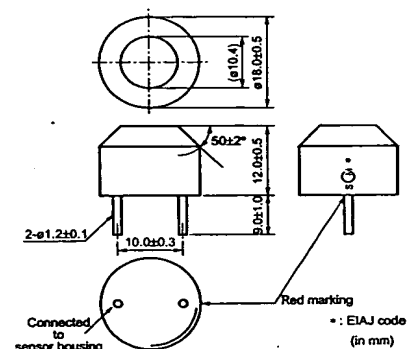
Back sonar of automobiles, Parking meters, Water level meters.



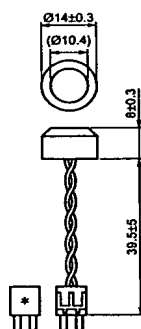
MA40E7R/S



MA40E7S-1

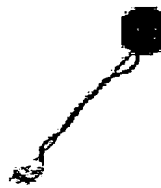


MA40E8-2

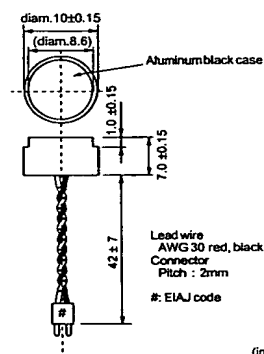


Lead wire : AWG30, Red, Black  
Connector Pitch : 2mm  
\*: EIAJ code

(in mm)



MA40MC10-1B



(in mm)

Part Number	Construction	Using Method	Nominal Freq. (kHz)	Overall Sensitivity	Sensitivity (dB)	S.P.L (dB)	Directivity (°)	Cap. (pF)	Operating Temp. Range (°C)	Detectable Range (m)	Resolution (mm)	Max. Input Voltage (Vp-p)
MA40E7R	Water proof	Receiver	40	-	-74 min. (0dB=10V/Pa)	-	100	2200	-30 to 85	0.2 to 3	9	-
MA40E7S	Water proof	Transmitter	40	-	-	106 min. (0dB=0.02mPa)	100	2200	-30 to 85	0.2 to 3	9	100 Pulse width 0.4ms Interval 100ms
MA40E7S-1	Water proof	Dual Use	40	-	-72 min. (0dB=10V/Pa) : reference only	106 min. (0dB=0.02mPa)	75	2200	-30 to 85	0.2 to 3	9	100 Pulse width 0.4ms Interval 100ms
MA40E8-2	Water proof	Dual Use	40	-	-85 min. (0dB=10V/Pa)	106 min. (0dB=0.02mPa)	75	2800	-30 to 85	0.2 to 1.5	9	160 Pulse width 0.8ms Interval 60ms
MA40MC10-1B	Water proof	Dual Use	40	-	-86 min. (0dB=10V/Pa)	104 min. (0dB=0.02mPa)	100 typ.	2400	-30 to 85	0.2 to 1.5	9	160 Pulse width 0.8ms Interval 60ms

Distance:30cm, Overall sensitivity:0dB=10Vp-p, Sensitivity:0dB=1Vrms/ $\mu$ bar, Sound pressure level:0dB=2x10<sup>-4</sup> $\mu$ bar, 1 $\mu$ bar=0.1Pa

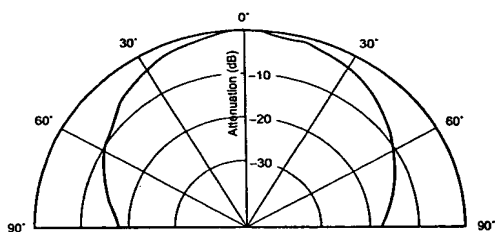
The sensor can be used in the operating temperature range.

Please refer to the individual specification for the temperature drift of Sensitivity/Sound pressure level or environmental characteristics in that temperature range.

Directivity, detectable range and resolution are typical values. They can be changed by application circuit and fixing method of the sensor.

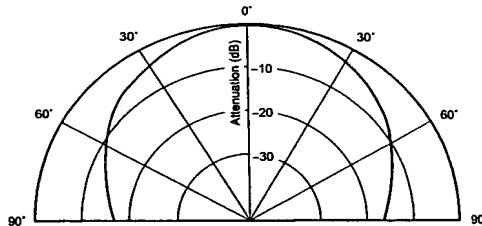
## ■ Directivity in Sensitivity

MA40E7R



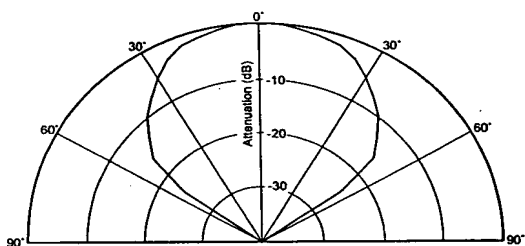
## ■ Directivity in S. P. L.

MA40E7S

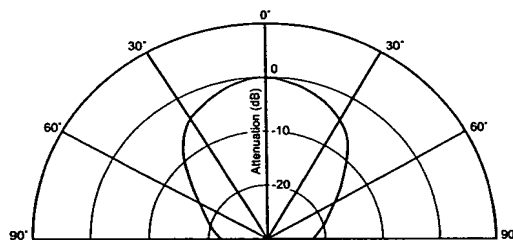


## ■ Directivity in Overall Sensitivity

MA40E7S-1

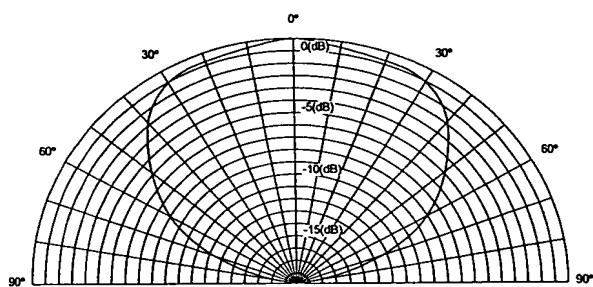


MA40E8-2



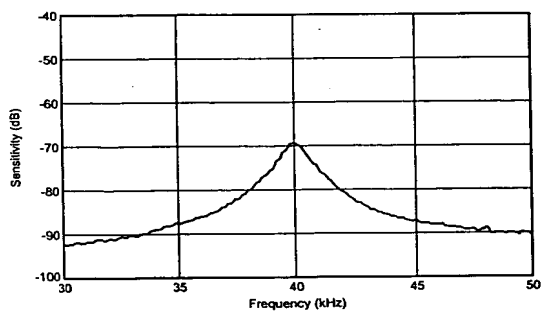
MA40MC10-1B

Beam Pattern



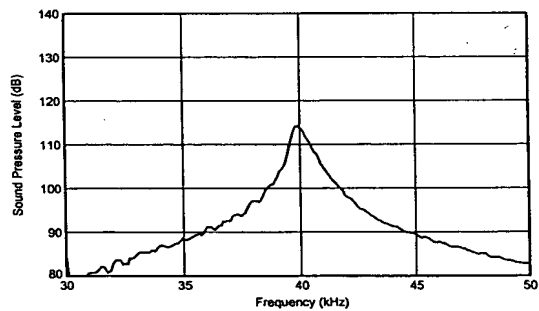
## ■ S. P. L. -Freq. Characteristics

MA40E7R



## ■ Sensitivity-Freq. Characteristics

MA40E7S





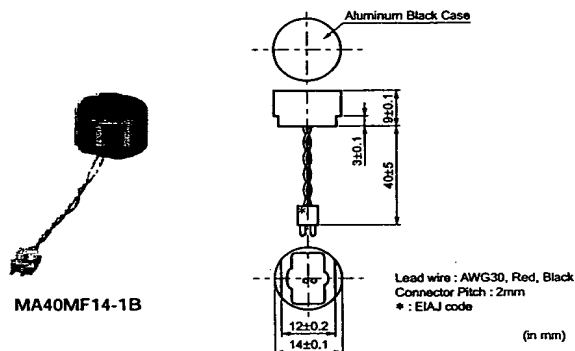
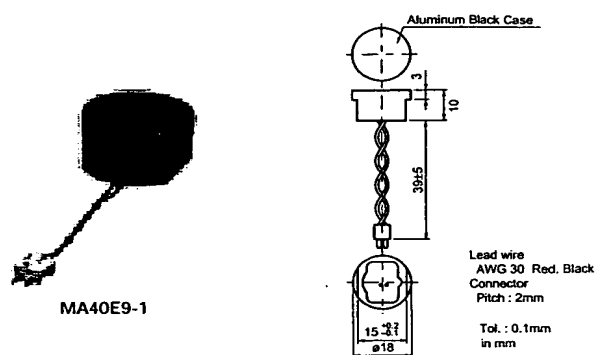
## Water Proof Type Asymmetric Directivity

### ■ Features

1. Compact and light weight.
2. High sensitivity and sound pressure.
3. Less power consumption.
4. High reliability.
5. Compressed directivity by itself

### ■ Applications

Vack sonar of automobiles, Parking meters, Water level meter.



Part Number	Construction	Using Method	Nominal Freq. (kHz)	Overall Sensitivity	Sensitivity (dB)	S.P.L (dB)	Directivity (°)	Cap. (pF)	Operating Temp. Range (°C)	Detectable Range (m)	Resolution (mm)	Max. Input Voltage (Vp-p)
MA40E9-1	Water proof	Dual Use	40	-	-85 min. (0dB=10V/Pa)	103 min. (0dB=0.02mPa)	100 x50°	4000	-30 to 85	0.2 to 1.5	9	160 Pulse width 0.8ms Interval 60ms
MA40MF14-1B	Water proof	Dual Use	40	-	-87 min. (0dB=10V/Pa)	103 min. (0dB=0.02mPa)	110 x50°	4400	-30 to 85	0.2 to 1.5	9	160 Pulse width 0.8ms Interval 60ms

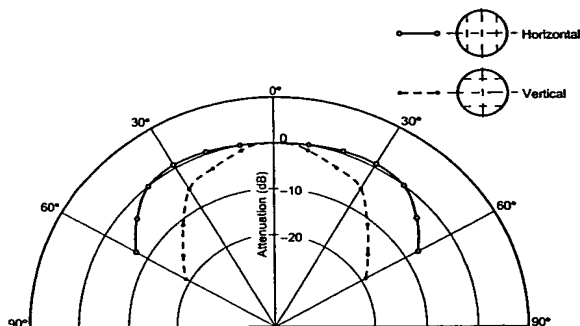
The sensor can be used in the operating temperature range.

Please refer to the individual specification for the temperature drift of Sensitivity/Sound pressure level or environmental characteristics in that temperature range.

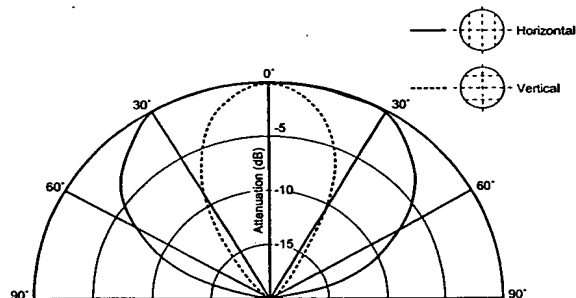
Directivity, detectable range and resolution are typical values. They can be changed by application circuit and fixing method of the sensor.

### ■ Directivity in Overall Sensitivity

MA40E9-1



MA40MF14-1B



## High-frequency Type

### ■ Features

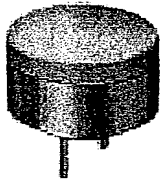
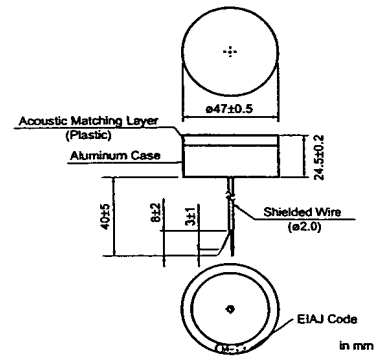
Using longitudinal vibration and matching with the air by acoustic matching layer, this type realized high sensitivity. Because of short wavelength, this type has sharp directivity and can be used high precise measurement.

### ■ Applications

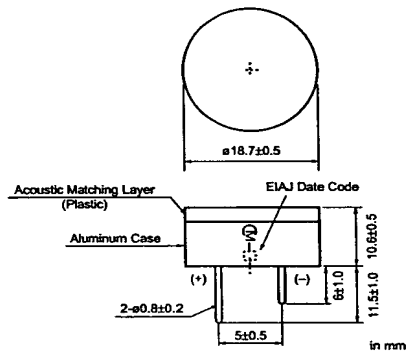
Approach switch for FA, Distance meter, Water or liquid level meters.



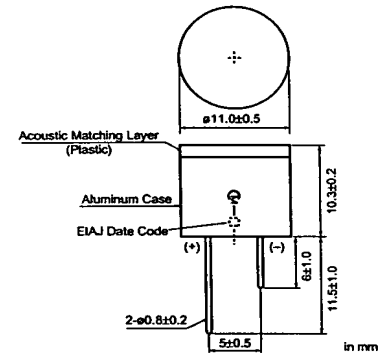
MA80A1



MA200A1



MA400A1



Part Number	Construction	Using Method	Nominal Freq. (kHz)	Overall Sensitivity (dB)	Sensitivity	S.P.L.	Directivity (°)	Cap.	Operating Temp. Range (°C)	Detectable Range (m)	Resolution (mm)	Max. Input Voltage (Vp-p)
MA80A1	High frequency type	Dual Use	75 +/-5	-47 min. 0dB=18Vpp (at 50cm)	-	-	7	-	-10 to 60	0.5 to 5	4	120 Pulse width 0.6ms Interval 50ms
MA200A1	High frequency type	Dual Use	200 +/-10	-54 min. 0dB=18Vpp (at 20cm)	-	-	7	-	-30 to 60	0.2 to 1	2	120 Pulse width 250μs Interval 20ms
MA400A1	High frequency type	Dual Use	400 +/-20	-74 min. 0dB=18Vpp (at 10cm)	-	-	7	-	-30 to 60	0.06 to 0.3	1	120 Pulse width 125μs Interval 10ms

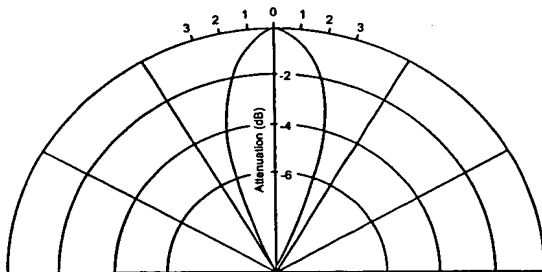
The sensor can be used in the operating temperature range.

Please refer to the individual specification for the temperature drift of Sensitivity/Sound pressure level or environmental characteristics in that temperature range.

Directivity, detectable range and resolution are typical values. They can be changed by application circuit and fixing method of the sensor.

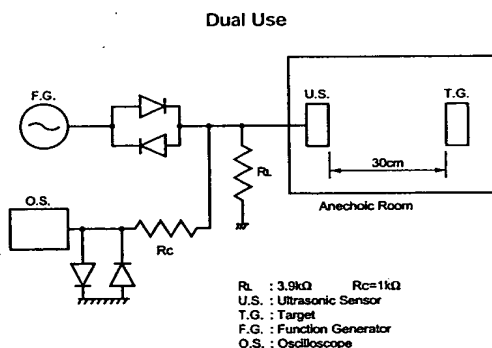
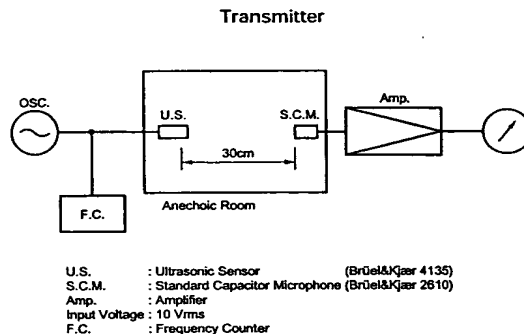
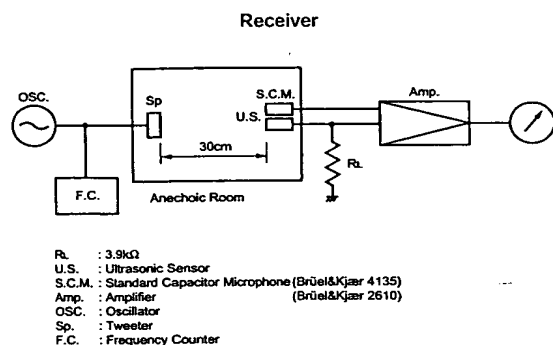
### ■ Directivity in Overall Sensitivity

MA\_A1 Series



## Data/Notice/Part Numbering

### ■ Test Circuit



5

### ■ Notice (Soldering and Mounting)

1. Pay attention to the mounting position as these sensors have directivity.
2. Please avoid applying DC-bias by connecting DC blocking capacitor or some other way because, otherwise, the component may be damaged.
3. Do not use in water.

### ● Part Numbering (The structure of the "Global Part Numbers" that have been adopted since June 2001 and the meaning of each code are described herein.) (If you have any questions about details, inquire at your usual Murata sales office or distributor.)

#### Ultrasonic Sensors

(Global Part Number) **MA** **40MF** **14** **-1N** **-M**

①      ②      ③      ④      ⑤

- ① Product ID
- ② Series
- ③ Characteristics
- ④ Individual Specification Code
- ⑤ Packaging

\* Global Part Number shows only an example which might be different from actual part number.  
\* Any other definitions than "①Product ID" might have different digit numbers from actual Global Part Number.

## Piezoelectric Ceramic Sensors (PIEZOTITE®)

**muRata**

### Shock Sensors

The shock sensor, PKGS series, is acceleration sensor with 2 terminals and detects acceleration & shock to be applied from outside, as electrical signal.

By bimorph piezo elements clamped at the two-end with original polarization technology, the shock sensor has high sensitivity and excellent durability.

The shock sensor is reflow solderable SMD type.

The shock sensor can have inclined primary axis so that appropriate shock sensor can be chosen for shock detection in HDD (Hard Disk Drive) and optical pick-up control in optical drive & optical-magnetic Drive.



#### ■ Features

1. Small size, low profile, high sensitivity and excellent durability.
2. Excellent linearity.
3. High resonance frequency and wide bandwidth.
4. Available tape and reel packaging.
5. Reflowable.
6. In addition to the voltage sensitivity type shock sensor (ME, LB and LC series), new type, the electrical charge sensitivity type shock sensor (NB, MF and LD series) are released. NB, MF and LD series have better anti-reflow temperature.

#### ■ Applications

1. HDD data writing protection, while shock is applied from outside.
2. Shock detection and protection in DVD, CD-R, CD-RW etc.
3. Pick-up control for disk type storage in Digital camera, Camcorder etc.
4. Other applications requiring acceleration detection.

### ■ Primary Axis Inclined Angle

The acceleration detection direction with the shock sensor can be inclined relative to the PCB. This inclination is called the primary-axis-inclined angle and can be selected from the four variations that are shown in the diagram on the right-0, 25, 45, and 90 degrees, respectively.

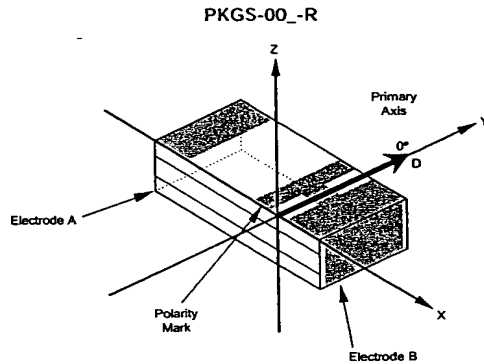
The acceleration detection sensitivity is greatest with the acceleration in the primary axis direction (direction D). With the 25- and 45-degree sensor types,

the detection sensitivity is available in both the Y and Z directions.

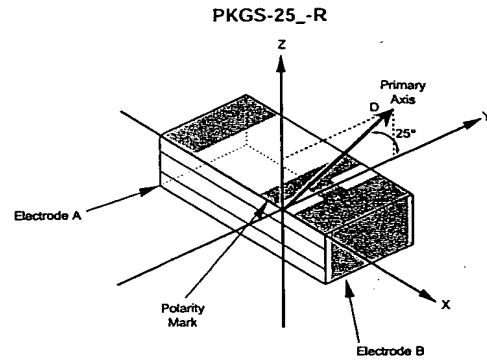
### ■ Polarity

The shock sensor has polarity. Referring to the diagram on the right, when acceleration is applied in direction D, a positive voltage (relative to the voltage on electrode A) occurs on electrode B.

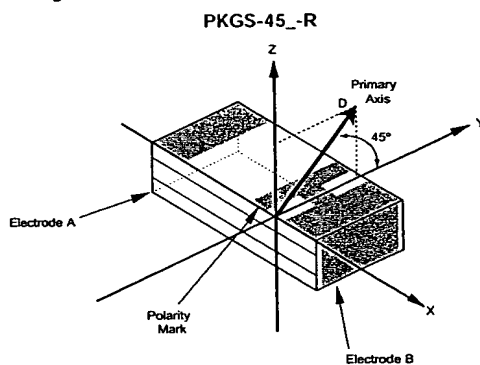
#### ■ Primary Axis Inclined Angle (0 degree)



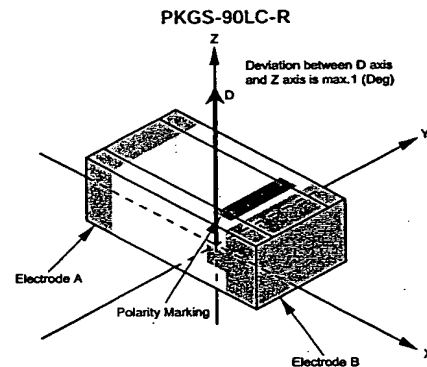
#### ■ Primary Axis Inclined Angle (25 degree)



#### ■ Primary Axis Inclined Angle (45 degree)



#### ■ Primary Axis Inclined Angle (90 degree)

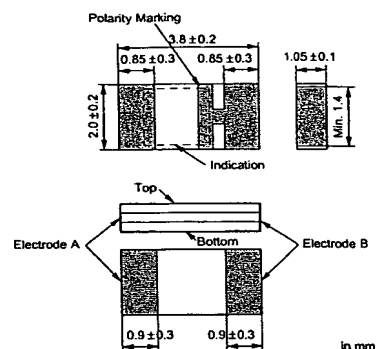


Under bar shown in part number is filled with two letters of Characteristics codes.

## Charge Sensitivity Type PKGS-\_NB-R



PKGS-\_NB-R



In mm

Part Number	Primary Axis Inclined Angle (°)	Sensitivity* (pC/G)	Capacitance (pF)	Insulation Resistance (M ohm)	Resonant Frequency (kHz)	Non-linearity (%)
PKGS-00NB-R	0	0.153 typ.	480 typ.	500 min.	44 typ.	1 typ.
PKGS-25NB-R	25	0.168 typ.	520 typ.	500 min.	44 typ.	1 typ.
PKGS-45NB-R	45	0.133 typ.	440 typ.	500 min.	43 typ.	1 typ.

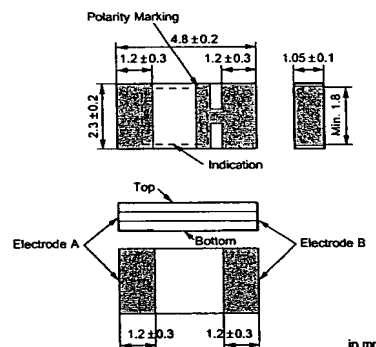
Operating Temperature Range : -40°C to 85°C Storage Temperature Range : -40°C to 85°C

\*1G=9.80665m/s<sup>2</sup>

## Charge Sensitivity Large Type PKGS-\_MF-R Series



PKGS-\_MF-R



In mm

Part Number	Primary Axis Inclined Angle (°)	Sensitivity* (pC/G)	Capacitance (pF)	Insulation Resistance (M ohm)	Resonant Frequency (kHz)	Non-linearity (%)
PKGS-00MF-R	0	0.325 typ.	570 typ.	500 min.	27 typ.	1 typ.
PKGS-25MF-R	25	0.350 typ.	610 typ.	500 min.	27 typ.	1 typ.
PKGS-45MF-R	45	0.285 typ.	490 typ.	500 min.	26 typ.	1 typ.

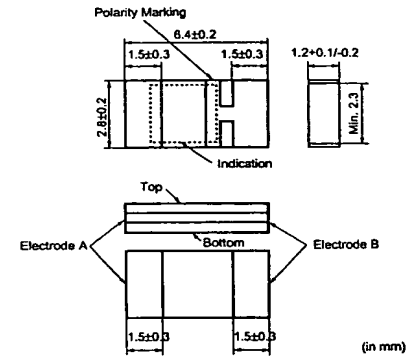
Operating Temperature Range : -40°C to 85°C Storage Temperature Range : -40°C to 85°C

\*1G=9.80665m/s<sup>2</sup>

## Charge Sensitivity Type PKGS-\_LD-R Series



PKGS-\_LD-R

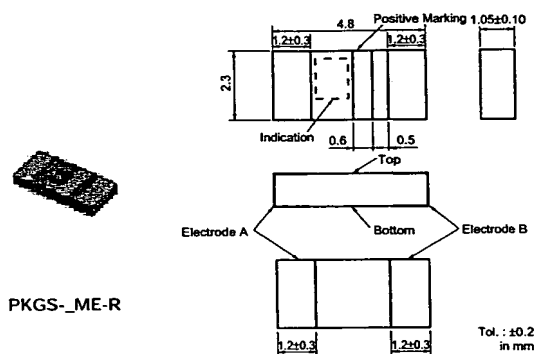


Part Number	Primary Axis Inclined Angle (°)	Sensitivity* (pC/G)	Capacitance (pF)	Insulation Resistance (M ohm)	Resonant Frequency (kHz)	Non-linearity (%)
PKGS-00LD-R	0	0.840 typ.	770 typ.	500 min.	20 typ.	1 typ.
PKGS-45LD-R	45	0.790 typ.	690 typ.	500 min.	18 typ.	1 typ.

Operating Temperature Range : -40°C to 85°C · Storage Temperature Range : -40°C to 85°C

\*1G=9.80665m/s<sup>2</sup>

## Voltage sensitivity Type PKGS-\_ME-R Series

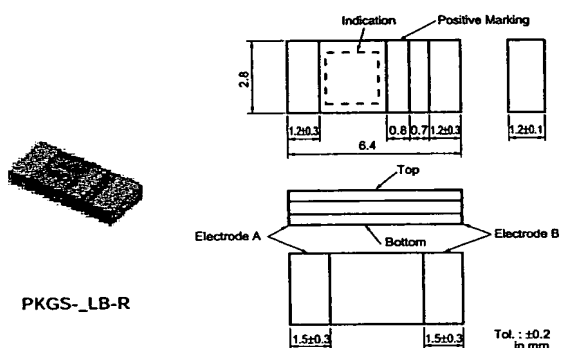


Part Number	Primary Axis Inclined Angle (°)	Sensitivity* (mV/G)	Capacitance (pF)	Insulation Resistance (M.ohm)	Resonant Frequency (kHz)	Non-linearity (%)
PKGS-00ME-R	0	1.00 typ.	160 typ.	500 min.	27 typ.	1 typ.
PKGS-25ME-R	25	1.0 typ.	170 typ.	500 min.	27 typ.	1 typ.
PKGS-45ME-R	45	1.00 typ.	210 typ.	500 min.	27 typ.	1 typ.

Operating Temperature Range : -40°C to 85°C Storage Temperature Range : -40°C to 85°C

\*1G=9.80665m/s<sup>2</sup>

## Voltage sensitivity Type PKGS-\_LB-R Series



Part Number	Primary Axis Inclined Angle (°)	Sensitivity* (mV/G)	Capacitance (pF)	Insulation Resistance (M.ohm)	Resonant Frequency (kHz)	Non-linearity (%)
PKGS-00LB-R	0	1.85 typ.	210 typ.	500 min.	20 typ.	1 typ.
PKGS-25LB-R	25	1.85 typ.	240 typ.	500 min.	20 typ.	1 typ.
PKGS-45LB-R	45	1.93 typ.	295 typ.	500 min.	20 typ.	1 typ.

Operating Temperature Range : -40°C to 85°C Storage Temperature Range : -40°C to 85°C

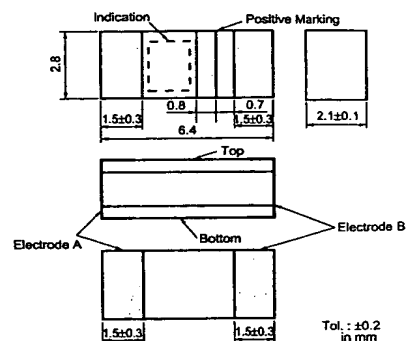
\*1G=9.80665m/s<sup>2</sup>



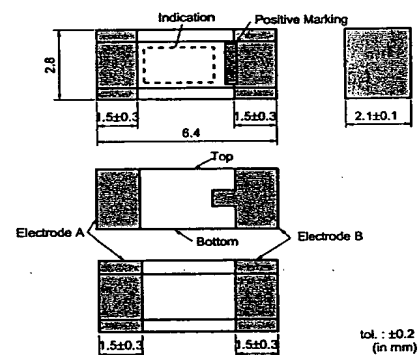
## Voltage sensitivity Type PKGS-LC-R Series



PKGS-00LC-R



PKGS-90LC-R



Part Number	Primary Axis Inclined Angle (°)	Sensitivity* (mV/G)	Capacitance (pF)	Insulation Resistance (M ohm)	Resonant Frequency (kHz)	Non-linearity (%)
PKGS-00LC-R	0	2.10 typ.	420 typ.	500 min.	20 typ.	1 typ.
PKGS-90LC-R	90	2.10 typ.	420 typ.	500 min.	20 typ.	1 typ.

Operating Temperature Range : -40°C to 85°C

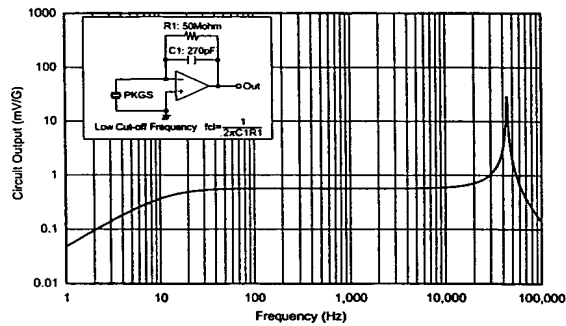
Storage Temperature Range : -40°C to 85°C

\*1G=9.80665m/s<sup>2</sup>

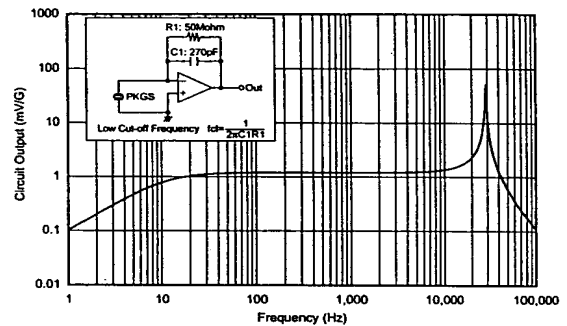
## Reference Data

### ■ Freq. Characteristics (Typical)

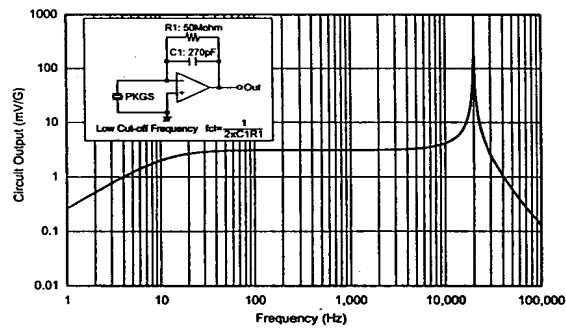
PKGS-\_NB-R



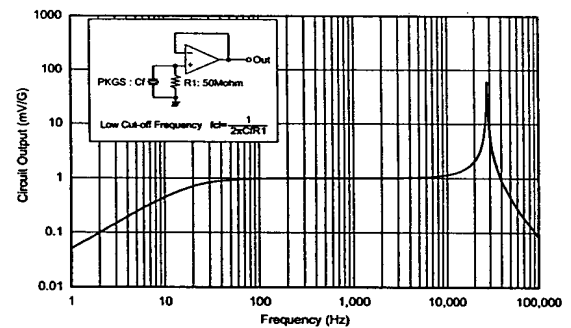
PKGS-\_MF-R



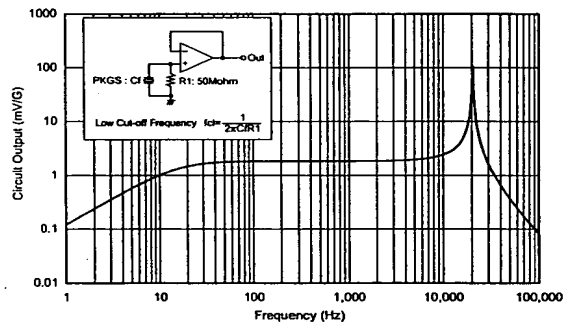
PKGS-\_LD-R



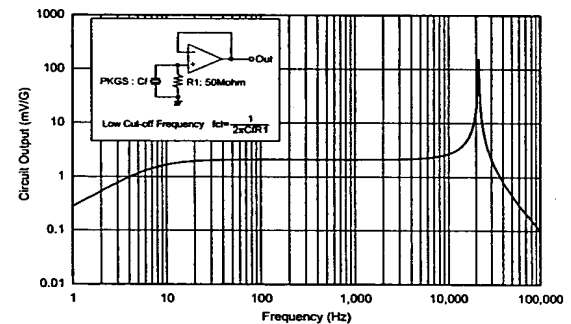
PKGS-\_ME-R



PKGS-\_LB-R



PKGS-\_LC-R

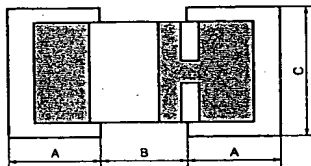


Under bar shown in part number is filled with two figures of inclined angle.

## PKGS Series Mounting/Notice/Part Numbering

### ■ Standard Land Pattern

Standard Land Pattern

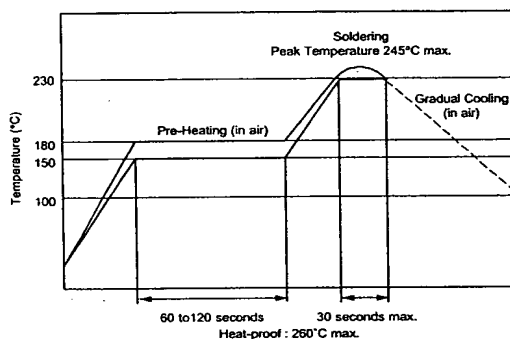


Dimensions

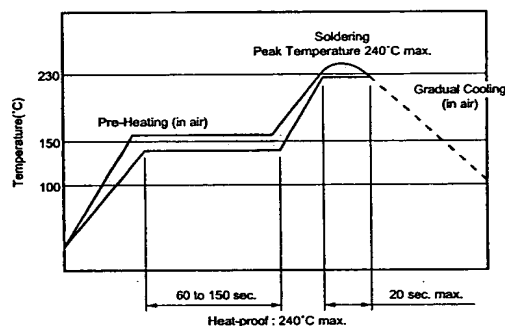
	PKGS-□□NB-R	PKGS-□□MF-R/ME-R	PKGS-□□LD-R/LB-R/LC-R
A	1.4 mm	1.7 mm	2.0 mm
B	2.0 mm	2.4 mm	3.4 mm
C	2.0 mm	2.3 mm	2.8 mm

### ■ Standard Reflow Profile

PKGS-□NB-R/MF-R/LD-R



PKGS-□ME-R/LB-R/LC-R



### ■ Notice (Rating)

Please do not apply DC voltage for this shock sensor.

### ■ Notice (Soldering and Mounting)

- Depending on the factors such as the system for securing the PCB or the rigidity of the vibration member, a new resonance system can occur, which adversely affects the accuracy of the acceleration measurement with the shock sensor.  
Therefore, be very careful to eliminate factors that can affect accuracy.
- Please inquire Murata for washing conditions.

### ● Part Numbering (The structure of the "Global Part Numbers" that have been adopted since June 2001 and the meaning of each code are described herein.) (If you have any questions about details, inquire at your usual Murata sales office or distributor.)

#### Shock Sensors

(Global Part Number) **PK** **GS-25** **ME** **1** **-R**

- ① Product ID
- ② Series
- ③ Characteristics
- ④ Individual Specification Code
- ⑤ Packaging

\* Global Part Number shows only an example which might be different from actual part number.

\*\* ③ "Characteristics", ④ "Individual Specification Code" and ⑤ "Packaging" might have different digit number from actual Global Part Number.

### ■ Minimum Quantity

PKGS- LC-R:180mm dir. reel/1500 pcs.

### ■ Dimensions of Reel



### ■ Dimensions of Taping



# Piezoelectric Ceramic Sensors (PIEZOTITE®)

**muRata**

## Shock Sensor

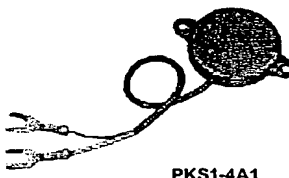
The piezoelectric element produces a voltage which is proportional to the acceleration of an impact or a vibration to which it is exposed. The shock sensor utilizes piezoelectric ceramics to convert the energy of impact into a proportional electrical signal. The piezoelectric shock sensor uses a "unimorph" diaphragm which consists of a piezoelectric ceramic disk laminated to a metal disk. The diaphragm is supported along its circumference in a housing. The sensor features compact, lightweight design, and is suitable for a wide range of applications requiring impact and vibration sensing.

### ■ Features

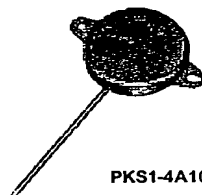
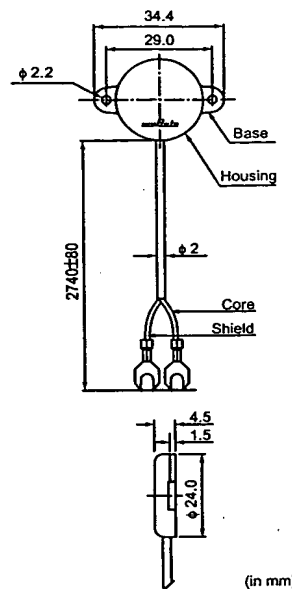
1. Compact, lightweight design.
2. High sensitivity assures it picks up even microlevel impact and vibration.
3. Rugged construction survive impact and vibration stresses.
4. Requires no bias voltage.

### ■ Applications

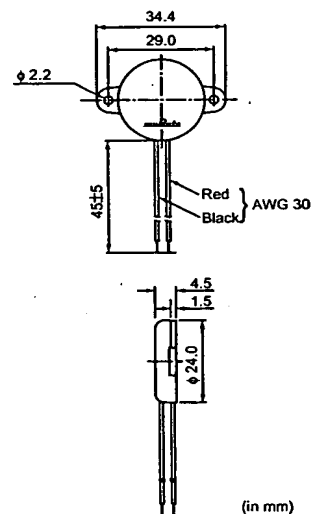
1. Car burglar sensors on doors.
2. Intruder sensors at windows or doors.
3. Burglar alarms for showcases and safes.
4. Vibration sensors for car audio equipment



PKS1-4A1



PKS1-4A10



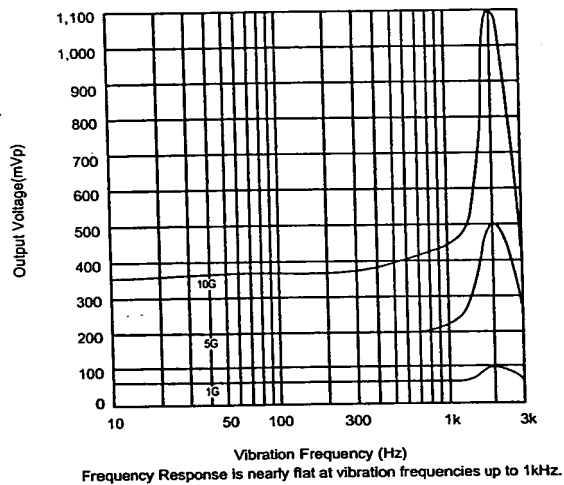
Part Number	Output Voltage	Capacitance	Insulation Resistance
PKS1-4A1	40mV0p /G TYP. 4.08mV0p/ (m/s <sup>2</sup> ) TYP. (at 25°C, 20MΩ Load, 10Hz - 1kHz)	10000pF±30%	30MΩmin. (at 100V D.C.)
PKS1-4A10		9000pF±30%	

1G=9.8m/s<sup>2</sup>

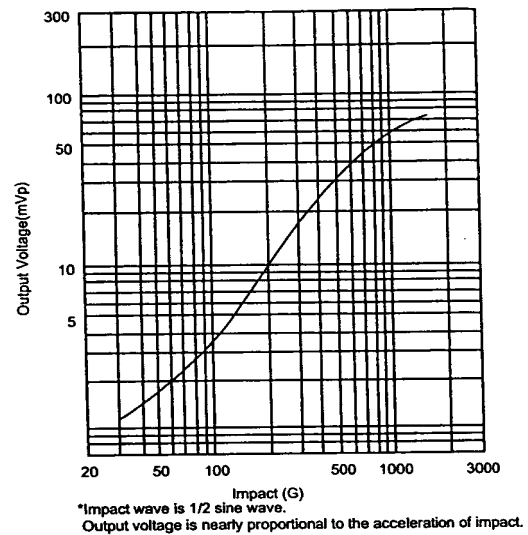
Output Voltage is reference value.

## ■ Characteristics Data

### ● Frequency Response



### ● Output Voltage vs. Impact Response



### ■ Notice

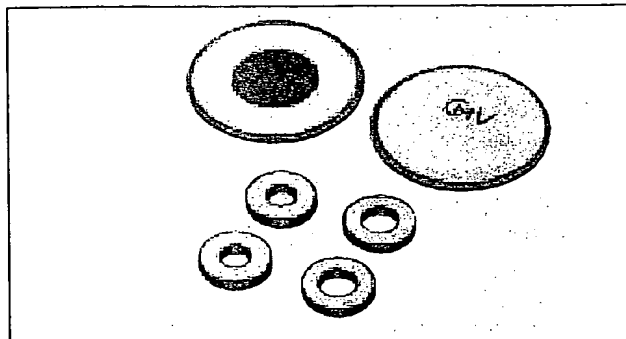
1. The component should be fixed at the place where the main axis of sensor has same direction as the vibration axis.
2. Please avoid applying DC-bias by connecting DC blocking capacitor or some other way because, otherwise, the component may be damaged.

# Piezoelectric Ceramic Sensors (PIEZOTITE®)

**muRata**

## Knocking Sensor Elements

The knocking sensor senses abnormal vibrations in an automobile engine. The sensor provides a feedback signal to the engine control system to suppress the knocking. Knocking sensors include a resonant type and a non-resonant type--both of which use piezoelectric elements. Murata offers highly-stable piezoelectric elements for use in knocking sensors which are directly mounted on the engine. Design emphasis is placed on heat-resistant, stress-resistant performance to ensure endurance in the harsh operation environment under the hood. Shape and dimensions are variable according to customer needs.



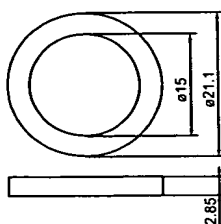
### ■ Features

1. Provides output voltage proportional to acceleration of vibration.
2. Flat frequency response makes these sensors applicable to any type of engine (for non-resonant type).

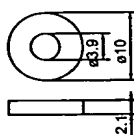
### ■ Applications

Knocking sensors for automobile engines.

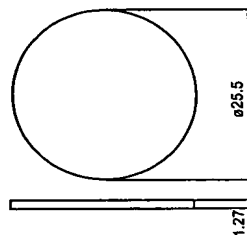
### ■ Dimensions (Typical value)



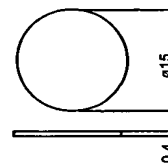
6CC-21-15-700



6CC-10-3R9-1000



7D-25-1600



7D-15-5400

(in mm)

Part Number	Resonant Frequency (kHz)	Capacitance (pF)	Electromechanical Coupling Coefficient (%)	Applications
6CC-21-15-700	66	450	18	Non-Resonant Type
6CC-10-3R9-1000	180	230	20	Non-Resonant Type
7D-25-1600	80	6300	45	Resonant Type
7D-15-5400	137	7200	55	Resonant Type

### ■ Notice

1. Do not touch the component with bare hand because the electrode may be damaged.
2. The component may be damaged if it is used in any application that deviates from its intended use noted within the specification.
3. Please avoid applying DC-bias by connecting DC blocking capacitor or some other way because, otherwise, the component may be damaged.

# Piezoelectric Ceramic Sensors (PIEZOTITE®)

**muRata**

## Ultrasonic Bubble Sensor

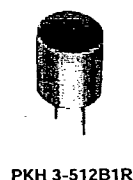
The ultrasonic bubble sensor emits an ultrasonic wave into a fluid then senses waves reflected from bubbles.

### ■ Features

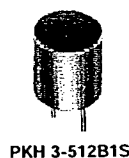
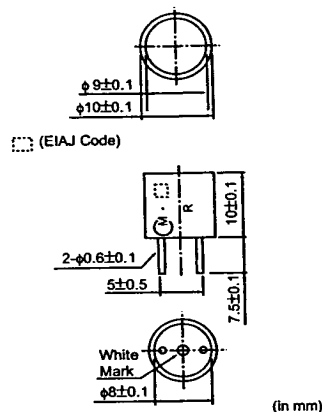
1. Small and light
2. High sensitivity
3. Low power consumption
4. High durability

### ■ Applications

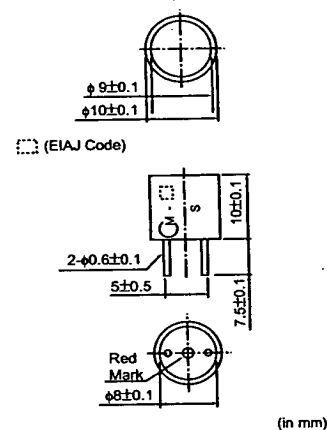
Senses the bubbles or fluids in tubes, e.g. vending machines.



PKH 3-512B1R

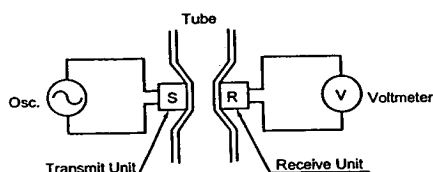


PKH 3-512B1S



Part Number	Nominal Frequency (kHz)	Capacitance (pF)	Electromechanical Coupling Coefficient (%)
PKH3-512B1R	512	280	55
PKH3-512B1S	512	220	56

### ■ Test Method



### ■ Notice

1. Please avoid applying DC-bias by connecting DC blocking capacitor or some other way because, otherwise, the component may be damaged.
2. Characteristics can be changed by fixing method. Please contact us.



# Piezoelectric Ceramic Sensors (PIEZOTITE®)

**muRata**

## Electric Potential Sensors

Every object has its own surface electrical charges or charges given to it from other objects. These electrical charges cause the object to have a certain electric potential with respect to other objects. The electric potential sensor is designed to measure this surface potential.

There are two major surface potential detection methods : The field-mill method and the vibrating capacitance method.

The former method synchronously shuts off the electrical flux from the object surface and modulates the electric field incident to the sensing electrode to induce an AC current on the electrode, proportional to the surface potential (DC). The latter method forms a capacitance across the surface of the object and the sensing electrode, and vibrates the sensing electrode vertically the surface of object to induce electrical charges which are proportional to the capacitance and surface potential, thereby obtaining an AC current proportional to the surface potential (DC).

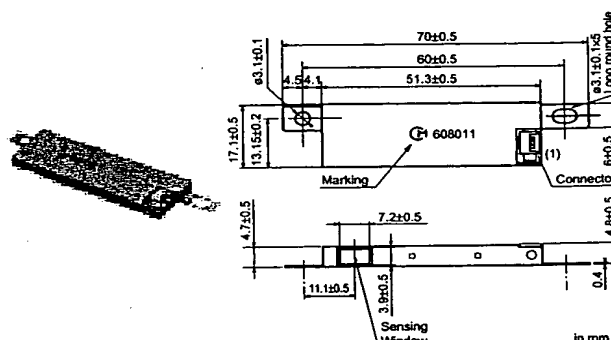
Murata's potential sensors, use a high-precision, piezoelectric tuning fork ("MICROFORK") with a proven production record, to achieve field shut-off vibration and electrode vibration. Integrating all of the signal processing circuit, Murata's electric potential sensor assures high operating stability and reliability.

### ■ Features

1. Compact, low-profile design.
2. DC voltage output.
3. High-precision liner output and highly stable.
4. Integrates all signal processing blocks, including oscillation, amplifying and rectifying circuit.

### ■ Applications

1. Sensing of surface electric potential for photosensitive drums used in PPC machines and laser beam printers.
2. High voltage measurement and detection for high voltage equipment.

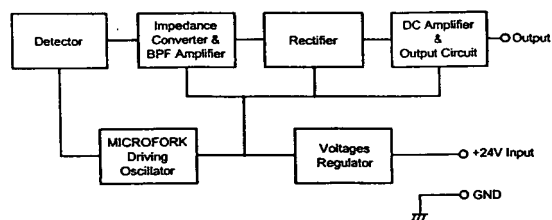


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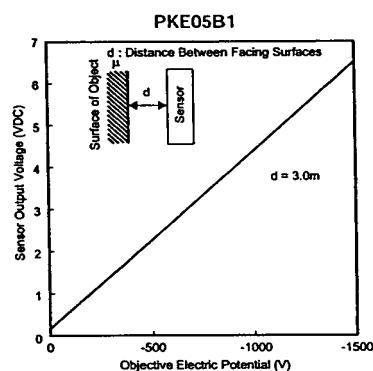
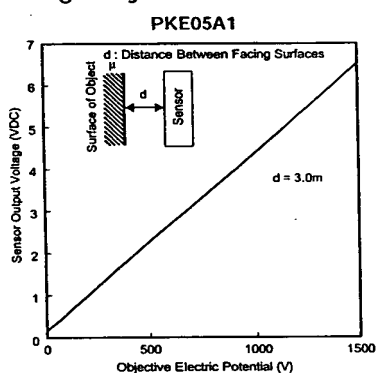
Part Number	Supply Voltage (Vdc)	Current Consumption (mA)	Min. Detectable Electric Potential (V)	Max. Detectable Electric Potential (V)	Output Voltage	Linearity (%)
PKE05A1	24 +/-10%	50 max.	0	1500	1/240Vdc of the objective potential	+/-1.5 max.(at 50V~1500V)
PKE05B1	24 +/-10%	50 max.	0	-1500	1/240Vdc of the objective potential	+/-1.5 max.(at -50V~-1500V)

Operation Temperature Range : 0°C to 60°C Storage Temperature Range : -30°C to 80°C  
Detection for negative electric potential are also available.

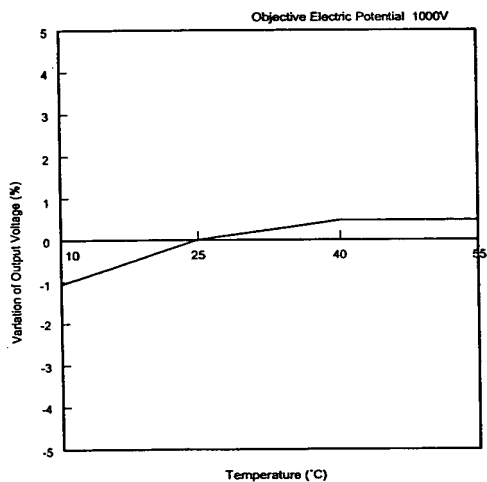
## ■ Circuit Configuration



## ■ Output Voltage-Objective Potential



## ■ Temperature Characteristics



## ■ Notice (Rating)

Using conditions such as source voltage, temperature range mentioned in this drawing should be kept.

## ■ Notice (Handling)

1. Electro-static voltage and excessive voltage or reverse voltage may damage the sensor.
2. The sensor should be kept from excessive shock.
3. Please insure the component is thoroughly evaluated in your application circuit because the output voltage and the distance are correlated.

## ● Part Numbering (The structure of the "Global Part Numbers" that have been adopted since June 2001 and the meaning of each code are described herein.) (If you have any questions about details, inquire at your usual Murata sales office or distributor.)

### Electric Potential Sensors

(Global Part Number) 

PK	E05	A	
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①      ②      ③      ④

- ① Product ID
- ② Series
- ③ Characteristics
- ④ Individual Specification Code

\* Global Part Number shows only an example which might be different from actual part number.

\* Any other definitions than "① Product ID" might have different digit number from actual Global Part Number.

**△Note:**

**1. Export Control**

(For customers outside Japan)

Murata products should not be used or sold for use in the development, production, stockpiling or utilization of any conventional weapons or mass-destructive weapons (nuclear weapons, chemical or biological weapons, or missiles), or any other weapons.

(For customers in Japan)

For products which are controlled items subject to the "Foreign Exchange and Foreign Trade Law" of Japan, the export license specified by the law is required for export.

**2. Please contact our sales representatives or product engineers before using our products listed in this catalog for the applications listed below which require especially high reliability for the prevention of defects which might directly cause damage to the third party's life, body or property, or when intending to use one of our products for other applications than specified in this catalog.**

- |                             |   |
|-----------------------------|---|
| ① Aircraft equipment        | ② Aerospace equipment   |
| ③ Undersea equipment        | ④ Power plant equipment   |
| ⑤ Medical equipment         | ⑥ Transportation equipment (vehicles, trains, ships, etc.)  |
| ⑦ Traffic signal equipment  | ⑧ Disaster prevention / crime prevention equipment  |
| ⑨ Data-processing equipment | ⑩ Application of similar complexity and/or reliability requirements to the applications listed in the above |

**3. Product specifications in this catalog are as of May 2002. They are subject to change or our products in it may be discontinued without advance notice. Please check with our sales representatives or product engineers before ordering. If there are any questions, please contact our sales representatives or product engineers.**

**4. Please read rating and △CAUTION (for storage and operating, rating, soldering and mounting, handling) in this catalog to prevent smoking and/or burning, etc.**

**5. This catalog has only typical specifications because there is no space for detailed specifications. Therefore, please approve our product specification or transact the approval sheet for product specification before ordering.**

**6. Please read CAUTION and Notice in this catalog for safety. This catalog has only typical specifications. Therefore you are requested to approve our product specification or to transact the approval sheet for product specification, before ordering.**

**7. Please note that unless otherwise specified, we shall assume no responsibility whatsoever for any conflict or dispute that may occur in connection with the effect of our and/or third party's intellectual property rights and other related rights in consideration of your using our products and/or information described or contained in our catalogs. In this connection, no representation shall be made to the effect that any third parties are authorized to use the rights mentioned above under licenses without our consent.**

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# Smart Ferroelectric Materials for Sensors and Mechatronic Device Applications

H.L.W. Chan

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The Hong Kong Polytechnic University  
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**Abstract** --- Ferroelectric single crystals, ceramics, polymers and composites can convert changes in mechanical and thermal energies into electrical signals as well as exhibiting the converse effect. This dual functional ability enables them to sense changes in their environment and actuate a desired response, which allow them to be regarded as smart (or intelligent) materials. The present paper reviews the piezoelectric and pyroelectric properties, poling behavior and transducer properties of selected numbers of ferroelectric materials studied in our laboratory. These include PMN-PT single crystals, ceramic/polymer 1-3 composites, 0-3 nanocomposites and ferroelectric films prepared by various methods. The uses of these materials in sensor and mechatronic device applications are also discussed.

respond to external change without assistance, and actively smart materials that utilize a feedback loop enabling them to both recognize the change and initiate an appropriate response through an actuator circuit. [1] Barium titanate PTCR (positive temperature coefficient of resistance) thermistors are passively smart materials capable of self-protection against over-current. Actively smart materials include vibration-damping systems for outer-space platforms and electrically-controlled automobile suspension systems.

In this paper, emphasis is placed on introducing the various smart materials studied in our laboratory which include ferroelectric single crystals of lead magnesium niobate-lead titanate (PMN-PT), ceramic/polymer 1-3 composites, 0-3 nanocomposites and ferroelectric films prepared by various methods. On-going projects on the uses of these materials in sensor and mechatronic device applications are also presented.

## I. INTRODUCTION

The concept of creating a form of materials and structures by providing the necessary functions of sensing, actuating, control and intelligence similar to a living being is the motivation for studying "smart materials". [1,2] Smart materials are functional materials for a variety of engineering applications and usually are part of some smart systems. For example, smart medical systems treating diabetes with blood sugar sensors and insulin delivery pumps; smart airplane wings achieving greater fuel efficiency by altering their shape in response to air pressure and flying speed; smart tennis rackets having rapid internal adjustments for overhead smashes and delicate drop shots and smart water purification systems for sensing and removing noxious pollutants. Many smart systems have been developed for automobiles, and there are many more to come.

Smart materials can be conveniently subdivided into passively smart materials that

## II. PMN-PT SINGLE CRYSTALS

The superior piezoelectric properties of relaxor-based ferroelectric single crystals such as  $\text{Pb}(\text{Zn}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-PbTiO}_3$  (PZN-PT) and  $\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-PbTiO}_3$  (PMN-PT) have attracted worldwide attention.[3,4] These crystals have ultrahigh piezoelectric coefficient ( $d_{33} > 1800$  pC/N) and electromechanical coupling coefficient ( $k_{33} > 0.9$ ), (for comparison, the commonly used piezoceramic lead zirconate titanate (PZT) has  $d_{33} \sim 300\text{-}500$  pC/N and  $k_{33} \sim 0.6$ ), and strain levels up to 0.5% with minimal hysteresis. It is thus believed that they will become the new generation materials for transducers and actuators. We have a collaborative project with the Shanghai Institute of Ceramics, Chinese Academy of Sciences (SICCAS) on PMN-PT single crystals in which

the crystals provided by SICCAS are characterized and then used in transducer developments. High frequency medical transducer for intravascular ultrasonography (IVUS) is one type of transducer under investigation. The crystal transducers will be developed jointly with a company in USA to be used in their IVUS systems. We will also grow these crystals in our laboratory and study the structural-property relationship using TEM and SEM. These crystals are also very promising actuator materials to be incorporated into various smart systems for industrial applications.

### III. CERAMIC/POLYMER 1-3 COMPOSITES

1-3 composites consisting of piezoelectric ceramic rods embedded in a polymer matrix (Fig. 1) have found many fruitful applications in medical and underwater ultrasound.[5,6] Compared to ceramics, they have much lower acoustic impedance, hence energy can couple better to human tissue and water. They have higher hydrostatic  $d_h$  coefficient for underwater hydrophone application and good acoustic isolation between elements when used in ultrasonic arrays for medical imaging. Analogous to a photonic bandgap material, 1-3 composites have stopband resonances and if designed properly, acoustic waves will not be able to propagate in the plane of a composite disk and all the input energy can only radiate in a forward direction, hence eliminating the artifacts caused by the planar coupling effect and enhance the efficiency of the transducer. We have studied the resonance characteristics of 1-3 composites and are designing ultrasonic transducers using these materials.[7,8]

Recently, 1-3 composites have found useful applications in ultrasonic wire bonding. By using these materials, spurious resonance modes are suppressed and the thickness mode resonance has lower Q, which improves the stability of the transducer during bonding operations. [9] It has also opened up opportunities for designing transducers with higher frequencies or with multiple frequencies. A sensor that provides feedback signal to indicate the bond quality can also be installed [10] and a "smart" bonding transducer can be produced. Another on-going project is to fabricate high-frequency 1-3 composites for IVUS application. A sol-gel process is used to prepare piezoceramic fibres with diameter ranging from 30  $\mu\text{m}$  to 50  $\mu\text{m}$ . Aligned fibres are inserted into a low-viscosity

epoxy enclosed in a plastic cylinder mold. By using different amounts of fibres, composites with different ceramic volume fractions are produced. The composites are then sliced into disk-shaped samples and, after poling, used in IVUS transducer fabrication.

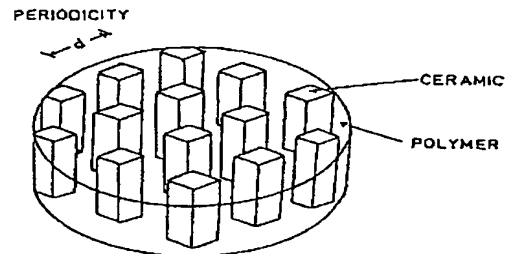


Fig. 1. Schematic diagram of ceramic/polymer 1-3 composite.

### IV. CERAMIC/POLYMER 0-3 COMPOSITES

0-3 ceramic/polymer composites consisting of ceramic powder imbedded in a polymer matrix have also been studied extensively (Fig. 2). If both the ceramic and the polymer phases are ferroelectric, interesting properties are produced by poling the two phases in specific ways.[11] As the piezoelectric coefficients of the ceramic and copolymer phases have opposite signs while the pyroelectric coefficients have like signs, when both phases are poled in the same direction, the pyroelectric activity of the two phases reinforces while their piezoelectric activity partially cancels. This is very useful for pyroelectric sensor application since the low piezoelectric activity in the sensing element can minimize the vibration induced noise in the sensor. When the ceramic and polymer phases are poled in opposite directions, their piezoelectric activity reinforces while the pyroelectric activity partially cancels. This makes the 0-3 composite a suitable hydrophone material. [12] In order to use the 0-3 composites for integrated sensor applications, nanosized ceramic powders are produced by sol-gel processes and the powders are then incorporated into a polymer matrix to produce 0-3 nanocomposites. We have fabricated and characterized single-element pyroelectric sensors with different configurations and  $8 \times 1$  integrated pyroelectric array sensors with readout electronics (Fig. 3). The performance of these sensors has proved to be superior to their counterpart with ferroelectric polymer elements. We are

planning to fabricate 2-dimensional integrated nanocomposite arrays in collaboration with other research groups.

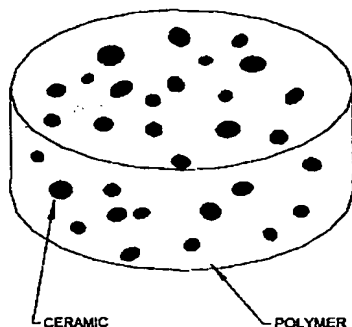


Fig. 2. Schematic diagram of ceramic/polymer 0-3 composite.

## V. FERROELECTRIC FILMS

The possibility of using ferroelectric thin films (thickness ~ several tens of nm) in memory applications have attracted considerable interests and there are many reports on the production and characterization of potentially useful thin films such as lead zirconate titanate (PZT) barium strontium titanate (BST) and strontium bismuth tantalate (SBT). On the other hand, development on microelectromechanical systems (MEMS) has called for the use of thicker (thickness > 1  $\mu\text{m}$ ) ferroelectric films. In our laboratory, we have on-

going projects on fabricating thin films by laser ablation, magnetron sputtering and by sol-gel routes. Thicker films can also be produced by a modified sol-gel process, or by doctor-blade tape casting etc. The devices under investigation include ultrasonic motors, multilayered piezoelectric transformers and actuators. Potential industrial applications have been identified and designs of these devices will be developed to cater for specific needs.

## VI. CONCLUSION

This brief overview describes the research and development activities undertaken in the "Centre for Smart Materials" at the Hong Kong Polytechnic University. It is envisaged that more industrial applications will be identified and the Centre will become a resource for researchers and engineers who are interested in pursuing the applications of "Smart Materials".

## ACKNOWLEDGEMENTS

Financial supports from the Hong Kong Polytechnic University "Areas of Strategic Development" (ASD) Fund, the Industrial Support Fund (ISD) and the Research Grants Council of the Hong Kong Special Administrative Region (Project No. PolyU5159/98P) are gratefully acknowledged.

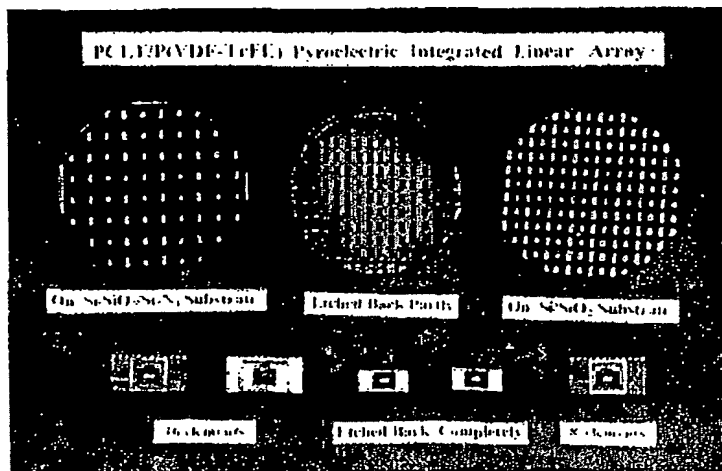


Fig. 3. PCLT/P(VDF-TrFE) pyroelectric integrated linear array.

# REFERENCES

- [1] R.E. Newnham, "Smart, Very Smart, and Intelligent Materials", *MRS Bulletin*, p.24, April, 1993.
- [2] R.E. Newnham and G.R. Ruschau, "Smart Electroceramics", *Am. Ceram. Soc. Bulletin*, vol. 75(10), p.51, 1996.
- [3] S.E. Park and T.R. Shrout, "Characteristics of Relaxor-Based Piezoelectric Single Crystals for Ultrasonic Transducers", *IEEE Trans. Ultrasonics, Ferroelectrics and Freq. Control*, vol. 44(5), p.1140, 1997.
- [4] S. Saitoh, T. Kobayashi, K. harada, S. Shimanuki and Y. Yamashita, "Forty-Channel Phased Array Ultrasonic Probe Using  $0.91\text{Pb}(\text{Zn}_{1/3}\text{Nb}_{2/3})\text{O}_3 - 0.09\text{PbTiO}_3$  Single Crystal", *IEEE Trans. Ultrasonics, Ferroelectrics and Freq. Control*, vol. 46(1), p.152, (1999).
- [5] H.L.W. Chan, J. Unsworth and T. Bui, "Mode Coupling in Modified Lead Titanate/Polymer 1-3 Composites", *J. Appl. Phys.*, 65(4), Feb., p.1754-1758, (1989).
- [6] H.L.W. Chan and J. Unsworth, "Simple Model for Piezoelectric Ceramic/Polymer 1-3 Composites Used in Ultrasonic Transducer Applications" *IEEE Trans. Ultrason., Ferroelectrics & Freq. Control*, 36(4), July, p.434-44, (1989).
- [7] H. Taunaumang, I.L.Guy and H.L.W. Chan, "Electromechanical Properties of 1-3 Piezoelectric Ceramic/Piezoelectric Polymer Composites", *J. Appl.Phys.*, 76-1, p.484-489, (1994).
- [8] T. Bui, H.L.W. Chan and J. Unsworth, "Multifrequency Composite Ultrasonic Transducer System", *US Patent 4,963,782*, Oct. 16, (1990).
- [9] H.L.W. Chan, S.W. Or, K.C. Cheng and C.L. Choy, "Ultrasonic Transducer", *US Patent*, pending.
- [10] S.W. Or, H.L.W. Chan, V.L. Lo and C.W. Yuen, "Ultrasonic wire bond quality monitoring using piezoelectric sensors", *Sensors and Actuators A: Physical*, 65, p.69-75, (1998).
- [11] H.L.W. Chan, P.K.L. Ng and C.L. Choy, "Effect of poling procedure on the properties of lead zirconate/vinylidene fluoride-trifluoroethylene composites", *Applied Physics Letters*, in press.
- [12] H.L.W. Chan, S.T. Lau, K.W. Kwok, Q.Q. Zhang, Q.F. Zhou and C.L. Choy, "Nanocomposite Ultrasonic Hydrophones", *Sensors and Actuators A*, in press.



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# PIEZO- AND PYROELECTRICITY IN POLYMER ELECTRETS AND THEIR APPLICATIONS

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## Introduction

A dielectric material possessing quasi-permanent polarization which may originate from space charges and/or dipoles, is an electret [1]. Typical thin film polymer space charge electret materials [1] are polytetrafluoroethylene (FEP). The corresponding dipolar electret materials [2-9] are polyvinylidene fluoride, PVDF, its copolymer with trifluoroethylene P(VDF-TxFE), odd nylons [10] and several copolymers of vinylidene cyanide, VDCN [11]. The dipolar electrets display piezo- and pyroelectric responses. Biopolymers also possess piezoelectric properties but bioelectrets are generally inferior to PVDF and P(VDF-TxFE) electrets. The present paper reviews briefly the properties of PVDF, P(VDF-TxFE) odd nylon and VDCN electrets and some applications. Piezo- and Pyroelectricity in Polymers Piezo- and Pyroelectricity refer to changes in the internal polarization of a dielectric for small changes in stress and temperature. Of the 32 crystal classes only 20 of them have asymmetric crystal structure and these are piezoelectric. Ten of these twenty classes have a unique polar axis and they possess a spontaneous polarization and are pyroelectric. A restricted group of pyroelectrics are ferroelectric. PVDF and its copolymer P(VDF-TxFE) are ferroelectric and hence they are also pyroelectric and piezoelectric. The electroactive (i.e., piezo- and pyroelectricity) properties are induced in these materials by an application of appropriate high electric fields at suitable temperatures (i.e. poling) and the induced polarization is quasi-permanent after removal of the poling field.

Table 1 provides a comparison of piezo- and pyroelectric properties of a few polymers [8].

	Polyvinyl chloride	Nylon-11	PVDF	VDF-TFE
Specific heat $C_p$ (J/kg °K) $\times 10^3$	0.93	1.6	1.3	
Density $\rho$ (kgm <sup>-3</sup> ) $\times 10^3$	1.37	1.04	1.76	1.9
Dielectric constant ( $\epsilon$ )	3.5	3.7	12	15-20
Coupling factor, $k$			0.16	0.3
Piezoelectric charge constant $d_{31}$ ( $\times 10^{-12}$ C/N)	0.7	0.26	28	30
Piezoelectric voltage constant $g_{31}$ (Vm/N) $\times 10^{-2}$	2.3	0.8	26.4	15
Pyroelectric coefficient, $p$ (Cm <sup>-2</sup> K <sup>-1</sup> ) $\times 10^{-6}$	0.1	0.5	4	4
Pyroelectric figure of merit $p^2/(pC_p \epsilon_0 \epsilon)$ (Vm <sup>2</sup> J) $\times 10^{-4}$	253	917	1648	

It should also be mentioned that aromatic polymers with diphenyl methylene units, the piezoelectric content is approximately  $20 \text{ mC/m}^2$  which is stable up to  $200^\circ\text{C}$ . For aliphatic polymers with  $(\text{CH}_2)_5$  units, the piezoelectric content is  $8 \text{ mC/m}^2$  which is stable up to  $8 \text{ mC/m}^2$ .

The piezo- and pyroelectric coefficients of polymers are not as high as those of electro-ceramics, viz., Lithium tantalate, lithium niobate and barium titanates, but the ferroelectric polymer thin films, on the other hand, enjoy superior mechanical strength and better piezoelectric (dg-product) and pyroelectric (p/e) figure of merit where d- and g- are piezoelectric strain coefficient, p the pyroelectric coefficient and  $\epsilon$  the dielectric constant. The d- ( $\text{CN}^{-1}$ ) and g- ( $\text{Vm}^{-1}$ ) coefficients measure the performance of piezoelectric sensors in the receiver mode whereas the piezoelectric stress coefficients e- ( $\text{NV}^{-1}$ ) and h- ( $\text{NC}^{-1}$ ) are used to express the ability of the piezoelectric actuators in the transmitting mode. These four piezoelectric coefficients are not independent and are related thus,

$$\frac{d}{g} = \epsilon_0 \epsilon^x; \quad \frac{e}{h} = \epsilon_0 \epsilon^x \quad (1)$$

$$\frac{e}{d} = C^E; \quad \frac{h}{g} = C^D \quad (2)$$

where C is the elastic stiffness (stress per unit strain), E the electric field, D the dielectric displacement, x the strain, X the stress,  $\epsilon_0$  the free space permittivity and  $\epsilon$  the dielectric constant. Thus,

$$\frac{d_{31}}{g_{31}} = \epsilon_0 \epsilon_{33}^x \text{ and } \frac{e_{31}}{h_{31}} = \epsilon_0 \epsilon_{33}^x \quad (3)$$

Another important parameter characterizing a piezoelectric transducer is the electro-mechanical coupling factor k which is defined thus,

$$k^2 = \frac{\text{Electrical (mechanical) energy converted into mechanical (electrical) energy}}{\text{Input electrical (mechanical) energy}} \quad (4)$$

$k^2$  is, of course, less than 1. For most applications, it is desirable to have a high value of k as it is a measure of the ability of a transducer to convert readily energy from one form into another. The permittivity  $\epsilon$  and k are related thus,

$$\epsilon_{33}^x = \epsilon_{33}^s (1 - k_{33}^2) \quad (5)$$

For hydrophone applications  $d_{33}$  - coefficients should be as high as possible, whereas for bimorph actuators  $d_{31}$  - coefficient is desired to be high.

The pyroelectric coefficient  $p$ , is given by,

$$p = \left( \frac{\partial P}{\partial T} \right)_{E,X} \quad (6)$$

High pyroelectric coefficients ( $\sim 280 \times 10^{-6} \text{ C m}^{-2} \text{ K}^{-1}$  at 20%) are observed with ferroelectrics possessing second order phase transitions, such as triglycine sulphate (TGS). Materials, such as strontium modified barium titanate (BST), which have quite a steep first order phase transition, are not suitable for pyroelectric sensors because they show a hysteresis behaviour with their transition temperature on thermal cycling. High permittivity ferroelectrics possessing desirable piezoelectric coefficients may not be ideal ferroelectric materials for pyroelectric applications for the following reasons. First, for practical purposes it is of advantage to provide a good match to the low input capacitance of the field effect transistors (FET) which is coupled to the pyroelectric sensing materials. Secondly, as stated earlier, a high figure of merit  $\left( \frac{p}{\epsilon} \right)$  can be achieved with polar materials with low permittivity, such as PVDF and P(VDF-TxFE).

#### Applications

The acoustic impedance of piezoelectric polymers is comparable to those of water and blood. Hence PVDF and its copolymer P(VDF-TxFE) electrets are useful for underwater and biomedical applications. Comprehensive reviews [13-16] for their applications have been published. Because of the limitation of space only a few specific applications will be reported here.

PVDF and its copolymer P(VDF-TxFE) offer many features for measuring shock-compression profiles, such as self powered operation, wide stress operating range and stress rate dependent output signals.

Ordinary shock-wave sensors, consisting of a quartz crystal as an active element, have resonant frequencies below 1 MHz and, therefore, are not suitable for measurement of shock-waves in liquids. It has been shown [17] that when a rapid load is applied to a piezoelectric film in a direction normal to the film thickness, the profile of the released charge, resulting from the film deformation, can be produced in a timescale of  $\leq 20 \text{ ns}$  with 95% accuracy. The piezo stress gauges are now used in shock loading applications including under water shock, gas gun impact, pulsed ion beam and etc [18].

Broadband ultrasonic transducers operating at 1-100 MHz with plane and curved focus can be made with PVDF films on transducer materials [19]. The mainfield of applications of these transducers lies in nondestructive ultrasonic testing. By bending the PVDF films, the focusing behaviour can be obtained and furthermore, by using a correction technique with Barker-coded [20] multilayer transducers, the sensitivity may be increased by a factor of 13 [19].

An important area of nondestructive testing is the detection of acoustic emission (AE) in solids. Discrete wave packets are generated when a solid is subjected to stresses at certain levels as a

result of a deformation of the material. This physical process of sound generation is known as the acoustic emission.

The atomic rearrangements that occur within a material during deformation and cracking generate elastic wave which propagate through the material and can be detected at a surface by piezoelectric transducers. The signals from the transducers can thus be used to detect deformation and cracks in solids structure under load. Furthermore several piezoelectric transducers can be used for the spatial location of the deformation within the structure. It is thus a useful nondestructive testing of structure. AE differs from most other nondestructive evaluation (NDE) in two significant ways. Firstly, the energy that is detected, is released from within the material under test, rather than being supplied externally. Secondly, the AE method is capable of detecting dynamic processes associated with the degradation of structural integrity.

Plate waves generated by AE sources propagate in two distinct modes, i.e. extensional and flexural. The extensional mode is a nondissipative process with higher frequencies and velocities than the dispersive flexural mode. A broad bandwidth piezoelectric polymer sensor should be able to detect the arrival of the extensional mode comprising of higher frequencies before the arrival of the flexural mode with its corresponding lower frequencies. Figure 1 shows the flexural and plate wave modes, detected by a ferroelectric ceramic/polymer composite AE sensor, embedded in a glass/epoxy laminate plate [21]. The sensitivity of the AE piezoelectric transducers is highest at their resonance frequencies which is governed by the thickness of the sensor material.

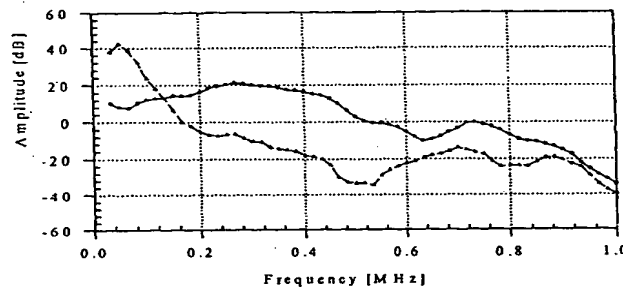


Figure 1 Flexural and extensional plate wave modes, detected by a ferroelectric ceramic/polymer composite piezoelectric transducer embedded in a glass/epoxy laminate [21].

Finally, PVDF piezoelectric sensors are suitable for applications up to 100°C whereas the odd nylons are applicable at high temperatures up to 200°C.

## References

1. G. M. Sessler,  
"Physical Principles in Electrets", in 'Topics in Applied Physics Electrets' second edition, ed. G. M. Sessler, Springer-Verlag, New York, Berlin, Heidelberg, Vol. 33, Chapter 2, pp 13-80, 1987.
2. M. G. Broadhurst and G. T. Davis,  
"Piezo- and Pyroelectric Properties", in 'Topics in Applied Physics Electrets', second edition, ed. G. M. Sessler, Springer-Verlag, New York, Berlin, Heidelberg, Vol. 33, Chapter 7, pp 285-319, 1987.
3. H. S. Nawa,  
"Recent Developments in Ferroelectric Polymers", J. Macromol. Sci., Rev. Macromol. Chem. Phys., Vol. C31, pp 341-431, 1991.
4. A. J. Lovinger,  
"Ferroelectric Polymers", Science, Vol. 220, pp 1115-1121, 1983.
5. A. J. Lovinger,  
"Developments in Crystalline Polymers", ed., D. C. Basset, J. Appl. Sci., Vol. 1, Chapter 5, 1982.
6. F. J. Callega, A. G. Arche, T. A. Ezquerro, C. Sautu Craz, F. Batallan, B. Frick and E. L. Cabarcos,  
"Structure and Properties of Ferroelectric, Copolymers of Poly (Vinylidene fluoride)", Adv. Polym. Sci., Vol. 108, 1993
7. D. K. Das-Gupta,  
"Pyroelectricity in Polymers", Ferroelectrics, Vol. 118, pp 165-189, 1991
8. D. K. Das-Gupta,  
"Piezoelectric and Pyroelectric Materials" in 'Molecular Electronics', ed. M. C. Petty, M.R. Bryce, and D. Bloor, Edward Arnold, London, Melbourne, Auckland, Chapter 3, pp 47-71, 1995.
9. D. K. Das-Gupta,  
"Piezoelectricity and Pyroelectricity" in 'Ferroelectric Polymers and Ceramic Polymer Composites' ed., D. K. Das-Gupta, Trans Tech Publisher, Zurich, Key Engineering Materials, Vol. 92-93, Chapter 1, pp 1-13, 1994
10. S. Nasr, J. Ducloux and M. Leduc,  
"PVDF Transducers Generating Scholte Waves" Electron. Lett., Vol. 24, pp 309-311, 1988
11. S. Miyata, M. Yokshikawa, S. Takaga and M. Ko.  
Ferroelectrics, Vol. 57, 267, 1984.

12. E. Fukada, T. Hattori, Y. Takahashi and M. Iijima,  
"Pyro/Piezo-Ferroelectric Properties of Aromatic and Aliphatic Polyarenes prepared by Vapour Phase Deposition Polymerization" Abstract, Polychar-3, Albuquerque, NM, USA, 1, 1995.
13. R. Gerhard-Multhaupt,  
"Electrets : Dielectrics with Quasi-permanent charge of Polarization", IEEE Trans, EI., Vol. 22, pp 531-554, 1987.
14. H. Ohigashi and H. Awano,  
"Studies on Design and Control of Functionalities in Thin Films of Ferroelectric Polymers", New Funct. Mater., Vol. C, pp 497-502, 1993.
15. Q. X. Chen and P. A. Payne,  
"Industrial Applications of Piezoelectric Polymer Transducers", Meas. Scie. Technol., Vol. 6, pp 249-267, 1995.
16. G. M. Sessler and J. E. West,  
"Applications" in 'Topics in Applied Physics Electrets', ed. G. M. Sessler, Springer-Verlag, New York, Berlin, Heidelberg, Second edition, Chapter 7, pp 347-382, 1987.
17. M. U. Anderson, R. A. Graham and D. E. Wackerbarth,  
"Prediction and Data Analysis of Current Pulses from Impact-Loaded Piezoelectric Polymers (PVDF)" in 'Shock Compression of Condensed Matter', ed., S. C. Schmidt, J. N. Johnson, L. W. Davison, Elsevier Scie. B. V., pp 805-808, 1989.
18. L. M. Lee, D. A. Hydman, R. P. Reed and F. Baner,  
"PVDF Applications in Shock Measurements", in 'Shock Compression of Condensed Matter', ed., S. C. Schmidt, J. N. Johnson and L. W. Davison, Elsevier Scie. B. V., pp 821-824, 1989.
19. M. Plate,  
"PVDF Ultrasonic Transducers", Ferroelectrics, Vol. 75, pp 327-337, 1987.
20. R. H. Barker,  
"Communication Theory, Butterworth, London, 273, 1953.
21. M. P. Wenger, P. Blanas, R. J. Shuford and D. K. Das-Gupta,  
"Acoustic Emission Signal Detection by Ceramic/Polymer Composite Piezoelectrets embedded in Glass-Epoxy Laminates" (To be published in Polymer Engineering and Science, 1996).

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